THE UNIVERSITY OF WARWICK

Library Declaration and Deposit Agreement

1. STUDENT DETAILS

Please complete the following:

Full name: ......STEPHEN......LAMBERT..

University ID number: ......0118848..

2. THESIS DEPOSIT

2.1 I understand that under my registration at the University, I am required to deposit my thesis with the University in BOTH hard copy and in digital format. The digital version should normally be saved as a single pdf file.

2.2 The hard copy will be housed in the University Library. The digital version will be deposited in the University's Institutional Repository (WRAP). Unless otherwise indicated (see 2.3 below) this will be made openly accessible on the Internet and will be supplied to the British Library to be made available online via its Electronic Theses Online Service (EThOS) service.
[At present, theses submitted for a Master's degree by Research (MA, MSc, LLM, MS or MMedSci) are not being deposited in WRAP and not being made available via EthOS. This may change in future.]

2.3 In exceptional circumstances, the Chair of the Board of Graduate Studies may grant permission for an embargo to be placed on public access to the hard copy thesis for a limited period. It is also possible to apply separately for an embargo on the digital version. (Further information is available in the *Guide to Examinations for Higher Degrees by Research*.)

2.4 *If you are depositing a thesis for a Master's degree by Research, please complete section (a) below. For all other research degrees, please complete both sections (a) and (b) below:*

(a) Hard Copy

I hereby deposit a hard copy of my thesis in the University Library to be made publicly available to readers ~~(please delete as appropriate) EITHER~~ immediately ~~OR after an embargo period of .... months/years as agreed by the Chair of the Board of Graduate Studies~~.

I agree that my thesis may be photocopied. YES ~~/ NO~~ (*Please delete as appropriate*)

(b) Digital Copy

I hereby deposit a digital copy of my thesis to be held in WRAP and made available via EThOS.

Please choose one of the following options:

EITHER My thesis can be made publicly available online. YES / ~~NO~~ (*Please delete as appropriate*)

OR My thesis can be made publicly available only after.....[date] (Please give date)
YES / NO (*Please delete as appropriate*)

OR My full thesis cannot be made publicly available online but I am submitting a separately identified additional, abridged version that can be made available online.
YES / NO (*Please delete as appropriate*)

OR My thesis cannot be made publicly available online. YES / NO (*Please delete as appropriate*)

3. GRANTING OF NON-EXCLUSIVE RIGHTS

Whether I deposit my Work personally or through an assistant or other agent, I agree to the following:

Rights granted to the University of Warwick and the British Library and the user of the thesis through this agreement are non-exclusive. I retain all rights in the thesis in its present version or future versions. I agree that the institutional repository administrators and the British Library or their agents may, without changing content, digitise and migrate the thesis to any medium or format for the purpose of future preservation and accessibility.

4. DECLARATIONS

(a) I DECLARE THAT:

- I am the author and owner of the copyright in the thesis and/or I have the authority of the authors and owners of the copyright in the thesis to make this agreement. Reproduction of any part of this thesis for teaching or in academic or other forms of publication is subject to the normal limitations on the use of copyrighted materials and to the proper and full acknowledgement of its source.

- The digital version of the thesis I am supplying is the same version as the final, hard-bound copy submitted in completion of my degree, once any minor corrections have been completed.

- I have exercised reasonable care to ensure that the thesis is original, and does not to the best of my knowledge break any UK law or other Intellectual Property Right, or contain any confidential material.

- I understand that, through the medium of the Internet, files will be available to automated agents, and may be searched and copied by, for example, text mining and plagiarism detection software.

(b) IF I HAVE AGREED (in Section 2 above) TO MAKE MY THESIS PUBLICLY AVAILABLE DIGITALLY, I ALSO DECLARE THAT:

- I grant the University of Warwick and the British Library a licence to make available on the Internet the thesis in digitised format through the Institutional Repository and through the British Library via the EThOS service.

- If my thesis does include any substantial subsidiary material owned by third-party copyright holders, I have sought and obtained permission to include it in any version of my thesis available in digital format and that this permission encompasses the rights that I have granted to the University of Warwick and to the British Library.

5. LEGAL INFRINGEMENTS

I understand that neither the University of Warwick nor the British Library have any obligation to take legal action on behalf of myself, or other rights holders, in the event of infringement of intellectual property rights, breach of contract or of any other right, in the thesis.

Please sign this agreement and return it to the Graduate School Office when you submit your thesis.

Student's signature: .... Date: ....19/08/2013....................

ADVANCING THE DEVELOPMENT OF HYBRID ELECTRIC VEHICLES IN MOTORSPORT

Innovation Report

Stephen Lambert

31st May 2013

ABSTRACT

Club motorsport, a low cost, amateur form of motorsport, forms a significant part of the motorsport industry in the United Kingdom. If efforts are not made to move towards more environmentally friendly technologies, then this form of motorsport is at risk of becoming irrelevant. One approach taken by other motorsport sectors has been to implement hybrid electric vehicle technology, which can result in improved vehicle performance on the race track. However, the companies that operate in the club motorsport sector do not typically have the resources and experience necessary to develop these technologies.

An innovative process was used to guide the design of a new hybrid electric vehicle drivetrain for use in club motorsport. This process made use of the ability for vehicle manufacturers to set the vehicle specifications in club motorsport. A conjoint analysis of customer requirements was carried out, a first for the industry, and led to the development of a market simulation tool. A vehicle simulation tool was then developed to assist in the evaluation of the hybrid electric drivetrain design options.

The result of following this process was a new and innovative hybrid electric drivetrain installed in a Westfield Sportscars Sport Turbo, reducing 0-60mph acceleration time from 5.4 seconds to 3.8 seconds. An innovative type of system control was implemented, by where the driver is given a finite amount of boost energy for use throughout the race. The drivetrain can also be easily transferred to other vehicle platforms, as the first shelf engineered hybrid drivetrain for motorsport, allowing its use by multiple manufacturers across the club motorsport and niche vehicle sectors.

This project has shown that it is possible to implement environmentally friendly technologies, such as hybrid electric vehicle technology, into club motorsport and be able to meet customer, technical and cost requirements. The process that has been developed enables innovation in hybrid electric race car design. This has been shown in the development of a hybrid electric vehicle suitable for use, and sale, in the club motorsport industry.

ACKNOWLEDGEMENTS

This work could not have been completed without funding from the Engineering and Physical Sciences Research Council (EPSRC) and the Warwick Innovative Manufacturing Research Centre (WIMRC), expertise on club motorsport and additional funding from Dr Paul Faithfull at Potenza Technology and academic support from Dr Steve Maggs, Adrian Vinsome and Dr Kevin Neailey at Warwick Manufacturing Group.

I would also like to thank my wife, Claire, and my son, Jackson for all their help and for putting up with the many hours of write up and for keeping me going throughout the whole process.

CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

ABS	Anti-lock Braking System
ALMS	American Le Mans Series
BMS	Battery Management System
BF	Benefit Factor
BHP	Brake Horse Power
CAD	Computer Aided Design
CAN	Controller Area Network
CVT	Continuously Variable Transmission
EDLC	Electric Double-Layer Capacitor
EDS	Electrical Distribution System
FIA	Fédération Internationale de l'Automobile
HEV	Hybrid Electric Vehicle
HF	Hybridisation Factor
ICE	Internal Combustion Engine
IVA	Individual Vehicle Approval
KERS	Kinetic Energy Recovery Systems
MPG	Miles Per Gallon
MSA	Motorsport Association
NiMH	Nickel Metal Hydride
SAE	Society of Automotive Engineers
SME	Small and Medium Enterprises
SMMT	Society of Motor Manufacturers and Traders
VCA	Vehicle Certification Agency
WIMRC	Warwick Innovative Manufacturing Centre
WMG	Warwick Manufacturing Group

1 INTRODUCTION

At the outset of this Engineering Doctorate, the aim was to produce an innovative product for the project partner, Potenza Technology. With increased pressure to innovate due to increasing significance of global environmental concerns, changing consumer attitudes and tough government targets to reduce the emissions of road transport, there had been a recent increase in hybrid electric vehicle development for road cars [1]. The first modern hybrid electric vehicle, the Toyota Prius, reached mass production in 1997, with the aim of doubling fuel economy and reducing tailpipe CO_2 emissions [2]. This, and other developments in the automotive industry, had left the development of hybrid electric vehicles in motorsport behind with very few examples in existence in 2006 when this doctorate began. This engineering doctorate was therefore seen as an opportunity to contribute to the innovation in the motorsport industry, highlighting hybrid electric vehicle technology as a viable drivetrain through the development of such a drivetrain and its installation into a prototype hybrid electric Westfield Sports Car.

This was achieved through the following objectives:

- Understand the technologies available for a hybrid drivetrain and analyse the success and failures of how this technology has been used to date in motorsport
- Understand the market for hybrid electric vehicles in club motorsport
- Identify the technical requirements for hybrid electric vehicle use in club motorsport
- Create an innovative hybrid electric drivetrain that meets these requirements
- Develop a design process that enables innovation in hybrid electric vehicle design for motorsport.

While it is necessary to investigate the use of technology in advancing the development of hybrid electric vehicles in motorsport, an emphasis is placed on current state of the art technology and how it can be used and integrated into a vehicle. In depth studies into the intricacies of these technologies, such as battery chemistry, motor design and control system design, were not undertaken. Only technologies available at the time have been considered and their benefits explored based on their potential use in club motorsport.

The scope of this project does not include the specific activities required to take this project through to production status. However, consideration for production build of the identified hybrid system was taken at the design and prototype stages.

Furthermore, the scope does not include specifying technical regulations should the system be adopted in a club motorsport series. However consideration was taken to ensure that the system would comply with the existing general safety regulations.

1.1 Project Partners

Potenza Technology is a Midlands based micro enterprise, as defined by the European Commission Small and Medium Enterprise (SME) definitions [3], with less than ten employees. Potenza Technology provides the engineering services for Potenza Sports Cars, a family owned business that acts as a holding company for a number of niche vehicle manufacturers. These include Westfield Sportscars, purchased in December 2006, GTM Cars, purchased in December 2007 and Roadster Bil AB, a Swedish race support, distribution and sports car manufacturing company, purchased in June 2008.

Due to financial constraints and changing business strategies, Potenza Technology withdrew from being sponsors of the Engineering Doctorate in April 2009. At this point, additional funding was sought from the WIMRC and an agreement was made to continue the project at Warwick Manufacturing Group (WMG), a department of the University of Warwick. A demonstrator vehicle was funded with Potenza Technology contributing standard Westfield Sportscars parts and the WIMRC funding all non-standard parts, such as motors, batteries and modifications to the standard Westfield Sportscars chassis.

1.2 Innovations

As a result of the work carried out within this Engineering Doctorate, a number of innovations were realised. This innovation report describes the work that was carried out to achieve these innovations. The innovations achieved were:

- A hybrid drivetrain designed for motorsport
- A ‘shelf engineered’ hybrid drivetrain, capable of use on other platforms
- A control system optimised to aid overtaking

- A racing concept with a set amount of energy for boost events
- A process for enabling innovation in hybrid drivetrains in motorsport
- The use of conjoint analysis within club motorsport
- The development of the Benefit Factor to compare hybrid architectures

2 METHODOLOGY

2.1 Introduction

The aim of this engineering doctorate was to contribute to the innovation in the motorsport industry, highlighting hybrid electric vehicle technology as a viable drivetrain through the development of such a drivetrain and its installation into a prototype hybrid electric Westfield Sports Car. This aim was defined by the identification of a potential gap in the market by the supporting company and the identification of the gap in the market as an opportunity to have a wider impact on the motorsport industry.

This was to be achieved through the following objectives:

- Understand the technologies available for a hybrid drivetrain and analyse the success and failures of how this technology has been used to date in motorsport
- Understand the market for hybrid electric vehicles in club motorsport
- Identify the technical requirements for hybrid electric vehicle use in club motorsport
- Create an innovative hybrid electric drivetrain that meets these requirements
- Develop a design process that enables innovation in hybrid electric vehicle design for motorsport.

On successful completion of these objectives, the output of the project was to be the development of an innovative hybrid electric vehicle drivetrain that:

- Increased vehicle performance when packaged within a standard Westfield Sportscars racing car
- Had the potential to be installed and increase the performance of other similar vehicles
- Was commercially viable
- Showed innovation within club motorsport
- Had an impact on the wider motorsport industry

The work carried out as part of this engineering doctorate is contained within a portfolio of submissions. This work is summarised within this Innovation Report.

2.2 Portfolio and Innovation Report Structure

To achieve the objectives of this Engineering Doctorate and realise the outcomes, the project was split into five phases, these were:

- Technology and Literature Review
- Requirements Capture and Analysis
- Technical Investigations
- System Design and Testing
- Process Design

These phases have been documented within six submissions and this Innovation Report, assembled during the course of this Engineering Doctorate. The portfolio also acts as a record of the work that was carried out. The title and date submitted for each submission is shown in Table 1.

Submission	Title	Submitted
1	Literature Review	24/07/2009
2	Requirements Capture and Analysis	30/11/2009
3	Identifying the Design Parameters for a Hybrid Electric Racing Car through Simulation	10/06/ 2010
4	Battery System Analysis and Testing	13/12/2010
5	Integration of a High Performance Hybrid Electric Drivetrain for Motorsport	20/05/2011
6	Published Papers and Articles	20/05/2011

Table 1. Portfolio Submissions

2.3 Technology and Literature Review

The first step in developing a hybrid electric vehicle drivetrain for motorsport was to understand the technology involved in developing such a vehicle and to look at how this technology has been previously implemented in motorsport. It was intended that this be achieved through a review of mostly academic literature. However, during the course of the submission, it was identified that due to confidentiality agreements and a lack of dissemination in the motorsport industry, the literature to be reviewed was mostly industrial.

Submission 1 [4] forms this review and documents the hybrid electric vehicles that have been used in motorsport and the relative success of these vehicles. It also discusses the potential vehicle design implications for a hybrid electric vehicle in motorsport. Submission 1 was completed in mid 2009, before Kinetic Energy Recovery Systems (KERS) had been successfully implemented in the Formula One World Championship and before the hybrid regulations for the Le Mans series of races were agreed. Therefore, this submission has been updated in this Innovation Report in Chapter 3, the Technology Review, and Chapter 4, the Literature Review.

The Technology Review aimed to present and understand the currently available technologies which would aid technology decisions for completion of this project. The intended outcome of the Literature Review was to gain an understanding of existing hybrid technologies in motorsport and to identify any suitable gaps in the industry that this project could exploit, identifying areas of potential innovation.

2.4 Requirements Capture and Analysis

Following analysis of hybrid electric vehicle technology use in motorsport and identification of any areas of potential innovation, the detailed requirements for the system were captured and analysed. To achieve this, four main stakeholders, with different requirements, were identified. These were the supporting company, the Motorsport Association (MSA), the Vehicle Certification Agency (VCA), and the customer.

The supporting company requirements were identified through an interview with the Managing Director of Potenza Technology. The requirements from the MSA and VCA were identified through further analysis of the literature. This work is presented in Submission 2 [5] and is summarised in Chapter 5 of this Innovation Report.

Submission 2 also contained the analysis of the customer requirements, which is split into two chapters in this Innovation Report. Chapter 6 presents the survey which was designed to understand the relative importance of vehicle attributes and additional extras to a potential customer. Chapter 7 documents the conjoint analysis of these attributes, the results of which were used to construct a market simulation tool compare two potential vehicle profiles.

There were two intended outputs of this phase. Firstly, a list of high level requirements to be considered in the development of the hybrid electric drivetrain and categorised according to importance. Secondly, the identification of the level of customer acceptance of hybrid electric vehicle technologies alongside potential price increases over the standard vehicle

2.5 Technical Investigations

Following the detailed capture and analysis of the project requirements, technical investigations were carried out to identify any technical barriers to implementation, leading to a high level design for the hybrid electric drivetrain. To achieve this, a vehicle simulation tool was developed to analyse the effect of different hybrid electric architectures, different electric motors and different energy storage device powers.

This was achieved through the development of a MATLAB/Simulink vehicle simulation tool and is detailed in Submission 3 [6]. Chapter 8 of this Innovation Report summarises the vehicle simulation tool, presenting a comparison of the simulation tool against the logged data of a standard vehicle. Chapter 9 compares the difference in performance of the different hybrid architectures, leading to the choice of hybrid architecture being made. Chapter 10 then uses the identified architecture to determine the most appropriate motor choice for the drivetrain.

The outcome of this phase was to have simulated the performance of different architectures and motors in a Westfield Sportscars platform and to have identified the high level design of the system by specifying the architecture and motor choice to be used by the hybrid electric drivetrain.

2.6 System Design and Testing

With the high level design identified, the detailed design and testing of the drivetrain was carried out, this included the design of the energy storage system and the integration of the drivetrain into a Westfield Sportscars chassis. The design of the energy storage device was determined through further use of the simulation tool and cell testing. The designed system, including motors, energy storage device and control systems, were then integrated into a Westfield Sportscars chassis to produce a prototype hybrid electric race car for testing.

The simulation, testing and design of the energy storage device is presented in Submission 4 [7]. A summary of the simulation of the energy storage system, leading to a selection of an energy storage type is presented in Chapter 11. The suitability of the energy storage type was verified through testing and design of the energy storage system. This is presented in Chapter 12. Submission 5 [8] details the integration and subsequent testing of the prototype hybrid electric race car and is summarised in Chapter 13 of this innovation report.

The intended outcome of this phase was to have designed, built and tested a prototype hybrid electric race car in order to analyse the suitability of the drivetrain and highlight and technical barriers to commercial implementation.

2.7 Process Design

Following the system design and testing phase, the learning from the project was analysed to determine how successfully the project requirements were met. . To allow similar future projects to benefit from the knowledge gained from this project; this information was then used to develop a design process for hybrid electric vehicles in motorsport. This is discussed in Chapter 14 of this Innovation Report, with the conclusions of the work presented in Chapter 15, including any recommendations for further work.

2.8 Published Papers and Articles

Submission 6 [9] documents published papers and articles that are based on the work of this Engineering Doctorate.

3 TECHNOLOGY REVIEW

3.1 Introduction

The aim of this chapter is to introduce a background to the type of technology used by hybrid and electric vehicles. In particular the relevance of a given technology to its potential use in hybrid electric vehicles in motorsport will also be demonstrated. Hybrid electric vehicle architectures will be presented, as well as energy storage systems and motor/inverter systems. The scope of this chapter does not include an analysis of how these technologies have been implemented in hybrid electric vehicles for motorsport as this is covered in the Literature Review chapter.

3.2 Hybrid Architecture Theory

Ehsani et al. define a hybrid powertrain as one containing two separate energy sources and converters, one able only to flow power out of the energy source (unidirectional) and one able to flow power in and out of the energy source (bidirectional) [10-12]. In the context of a hybrid electric vehicle (HEV) the unidirectional powertrain is an internal combustion engine (ICE) and the bidirectional powertrain is an electric machine with an electrical storage device.

This is illustrated in Figure 1 which shows a conceptual illustration of a hybrid drivetrain, according to Ehsani et al. [10]. It can be seen that Energy Source 1 and Energy Converter 1 represent the fuel tank and Internal Combustion Engine (ICE) in a HEV. The unidirectional power flow between them is chemical in nature. Energy Source 2 and Energy Converter 2 are bidirectional and therefore represent an electrical storage device and an electric machine in a HEV.

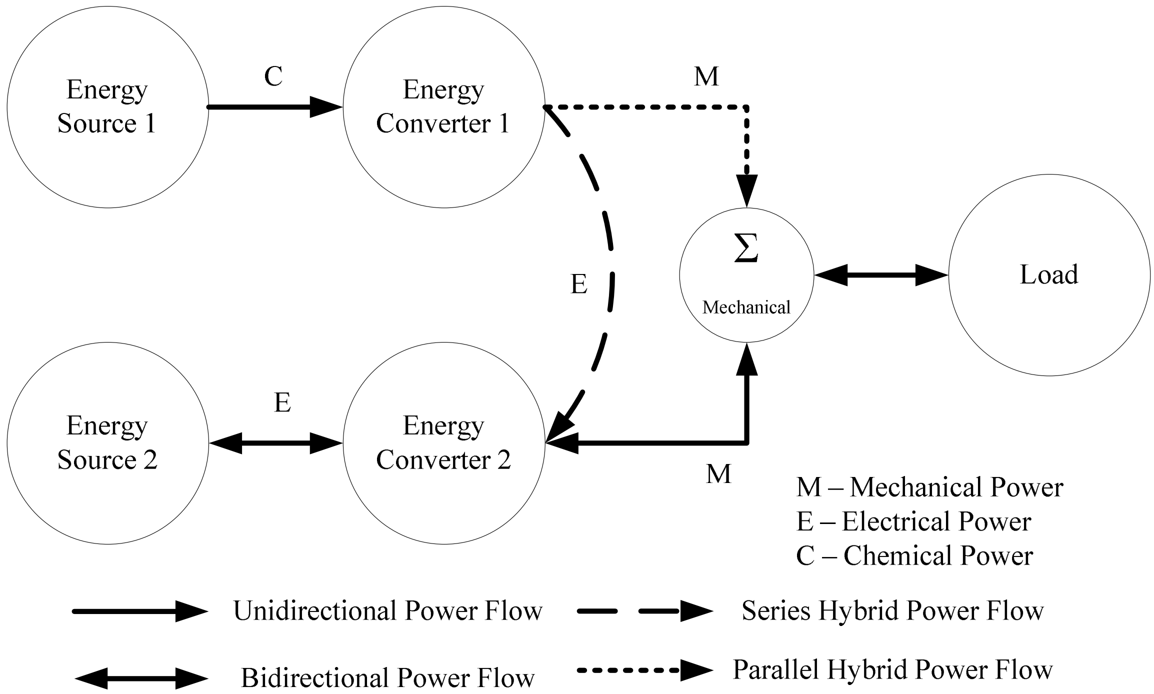


Figure 1. Conceptual Illustration of a Hybrid Powertrain, according to Ehsani et al. [10]

Ehsani et al. [10] also notes that a hybrid powertrain must contain a mechanical connection between the electric traction machine (Energy Convertor 2) and the load. Alongside this, it can be seen in Figure 1 that there are two alternative power flows from the ICE/generator (Energy Converter 1), either towards the load or towards the electric traction machine (Energy Converter 2) which define the nature of the hybrid architecture.

With just the power flow from Energy Convertor 1 towards the load; which must be capable of driving the vehicle and is therefore mechanical in nature; this example would be defined as a parallel hybrid architecture. With just the power flow from the ICE/generator (Energy Convertor 1) towards the electric traction machine; which is electrical in nature; this example would be defined as a series hybrid architecture. With both energy flows in place, Figure 1 can be defined as a combined hybrid architecture. Combined hybrid architectures (sometimes referred to as series-parallel hybrid architectures) are defined as architectures which can flow power in both the series hybrid configuration and the parallel hybrid configuration [10-12].

While the conceptual illustration shown in Figure 1 is a good method for explaining the power flow within a hybrid electric vehicle, the definition given by Ehsani et al. does not encompass all of the hybrid architectures possible. For example, there are hybrid powertrains that contain more than two separate energy sources and converters, which can be both unidirectional and bidirectional.

For example, Chan [13] defines a fourth architecture known as a complex hybrid architecture. The difference in architectures can be seen in Figure 2.

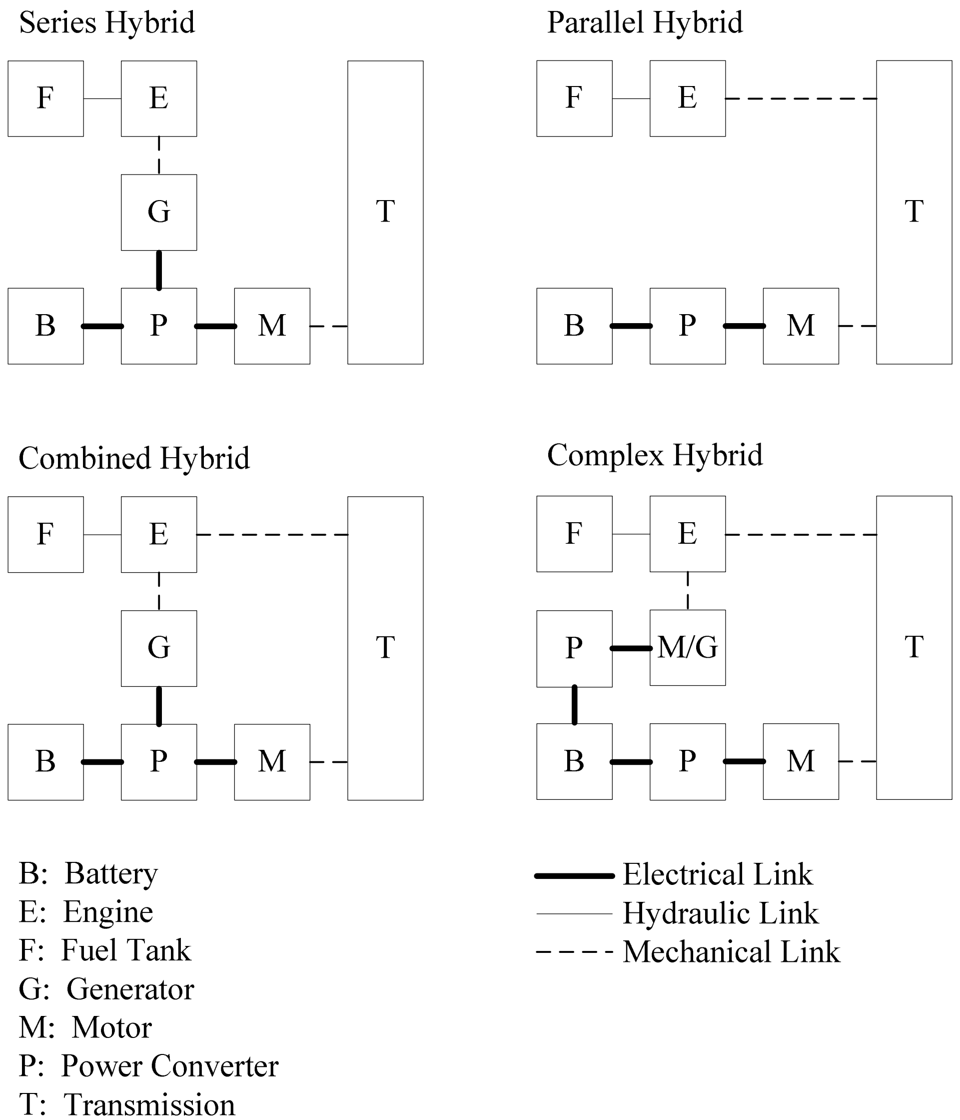


Figure 2. Hybrid Electric Vehicle Architecture Classifications, according to Chan [13]

By Chan's definition [13], a complex hybrid is similar in operation to a combined hybrid, however there is bidirectional power flow in the electric machine (as shown by being denoted as both a motor and generator) attached to the ICE in a complex hybrid unlike the unidirectional power flow in the combined hybrid from the electrical machine attached to the ICE.

To update Ehsani et al.'s [10] conceptual illustration (Figure 1) to also represent the complex hybrid architecture, an additional bidirectional electrical power flow must be added. As the fossil fuel power flow from Energy Source 1 is unidirectional, this additional power flow must be between Energy Convertor 1 and Energy Source 2 as demonstrated in Figure 3.

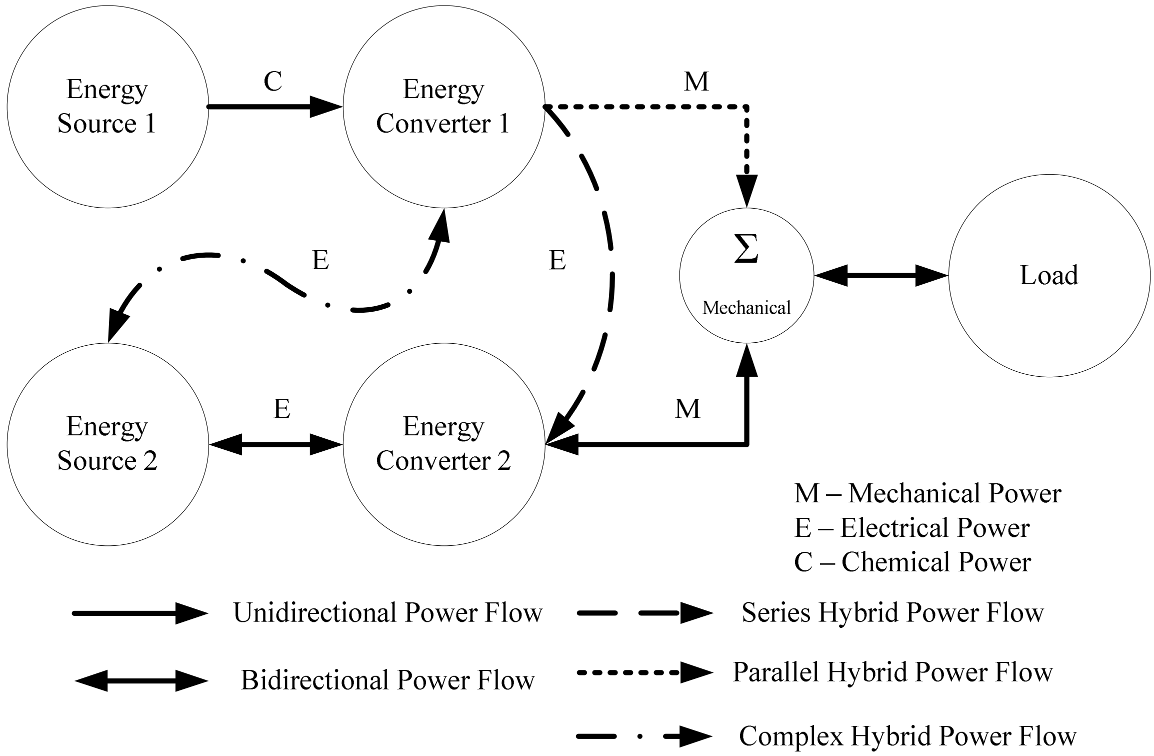


Figure 3. Conceptual Illustration of Power Flow in Hybrid Powertrains including Complex Powertrains

To work as a vehicle, a complex hybrid, as defined by Chan [13], must use either or both of the series and parallel power flows to transmit power to the load. Therefore according to Ehsani et al.'s definition this would be considered not a separate architecture but in fact a combined hybrid with an additional power flow between the two energy sources and energy converters.

Lo [14] supports Ehsani by also defining three types of hybrid architecture. However, Lo replaces the combined architecture with a complex architecture definition which has three sub-categories. The first complex hybrid sub-category shown in Figure 4 is defined as a series hybrid architecture with peak power unit. It can be seen that this is a series hybrid architecture with an additional energy source and converter in parallel with the electric machine in the form of a flywheel or similar. This is the only new sub category defined by Lo, as the second and third subcategories are identical to the combined and complex hybrid architectures referred to by Chan [13].

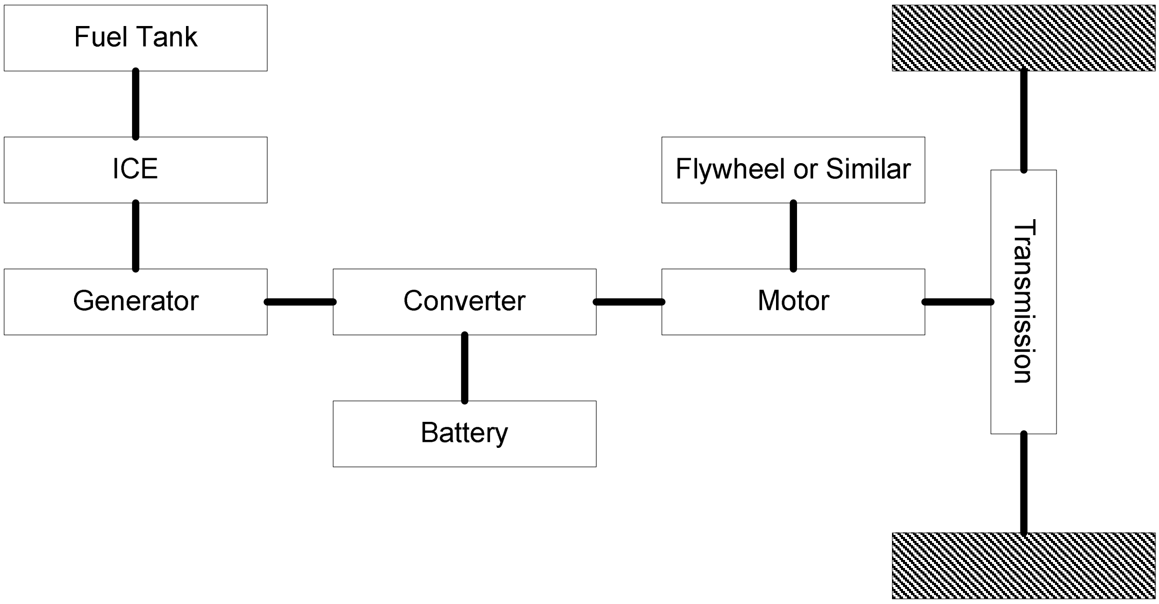


Figure 4. Series hybrid architecture with peak power unit, according to Lo [14]

From analysis of Figure 4 it is possible to further expand Ehsani et al.'s [10] conceptual illustration of a hybrid powertrain with the addition of optional extra energy sources and energy converters as shown in Figure 5.

Whilst Lo [14] defines this as a complex hybrid architecture, Figure 5 illustrates that this architecture can act in both parallel and series. It can therefore be defined instead as a combined hybrid architecture supporting Ehsani et al.'s assertion that there are only three possible hybrid architecture definitions: series, parallel and combined.

It is worth noting that it is theoretically possible to add any number of additional powertrains of power flows to a hybrid drivetrain and still maintain the three architecture definitions. An example of this is the Lotus EVE (Efficient, Viable, Environmental) technology demonstrator vehicle that includes both a 'micro hybrid' hybrid start stop system as well as a full parallel hybrid drive system [15].

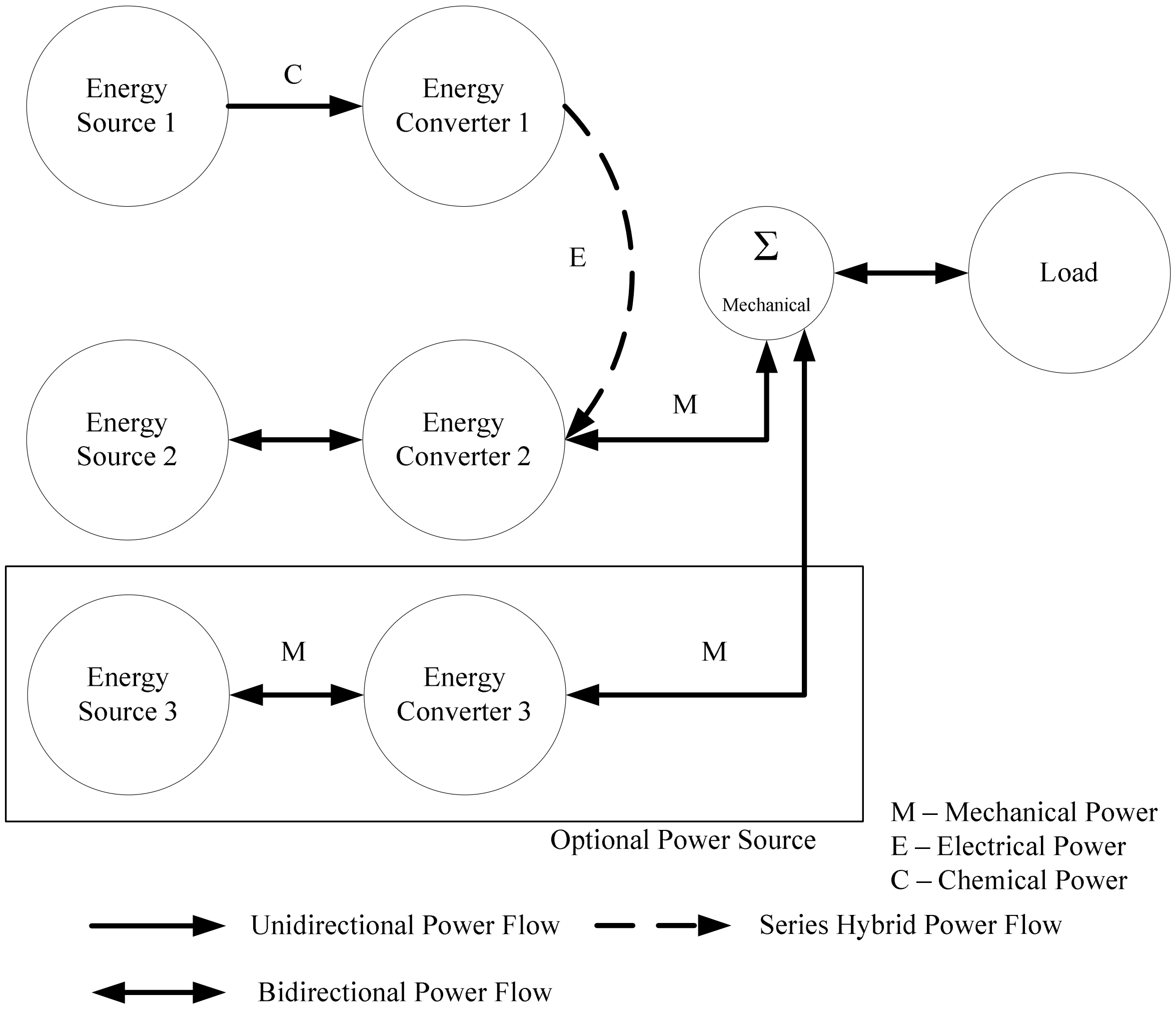


Figure 5. Conceptual Illustration of Power Flow in Hybrid Powertrains including an Optional Powertrain

As hybrid vehicle architectures emerge with more elaborate power flow configurations it is important to define the architecture based on the power flow around defined energy sources and energy converters. The conceptual illustration technique, as proposed by Ehsani et al. [10], provides a good way of doing this. Through this, the number of power flows contributing to the load can be counted and, based on the examples shown, if the number of mechanical power flows going from energy converters and directly to the load is greater than one, the architecture can be said to have parallel hybrid power flow.

If the total number of electrical or mechanical power flows from the energy converters is less than the number of power flows going from energy converters and directly to the load, then the architecture can be said to have series power flow. If the architecture has both series and parallel hybrid power flow, then the architecture can be said to be a combined architecture. It is therefore possible to define the complex hybrid architectures as either series, parallel or combined hybrid architectures. This technique will be used when considering the architectures that have previously been implemented in motorsport and determining the appropriate architecture choice for a Westfield Sportscars racing car.

3.3 Hybrid Architectures for a Westfield Sportscars Racing Car

There are three main types of Westfield Sportscars vehicles, the SE, the XI and the XTR. The XI, based on the Lotus Eleven, and the XTR are designed primarily for use on track days and are only produced in limited numbers. The SE is the most popular vehicle type that Westfield Sportscars sell and eligible to compete in cub racing in the British Automobile Racing Club Open Sportscars Championship. All of these vehicles are rear wheel drive and have only two seats. The SE and XI have engines mounted forward of the passenger compartment and the XTR has a mid mounted engine (rear of the passenger compartment). Figure 6 shows images of the different cars.

Figure 6. Westfield Sportscars Vehicle Types

Of each of these vehicle types, there are different variants, typically based on the engine used. For example there are two XTR models; one using a 1.3 litre Suzuki motorcycle engine and one using an Audi 1.8 litre turbo engine. The SE has four main variants, with varying engine options. The variants and engine options currently offered by Westfield Sportscars are shown in Table 2. In addition to the variants and engines shown, there are many other engines that are in use in Westfield Sportscars models due to cars being built at home in kit form.

SE Variants	Engines	Power
Sport Turbo	Vauxhall 1.6 Turbo Engine	145kW (195bhp)
Sport	1.6 Ford Sigma Engine	101kW (135bhp)
	1.6 Ford Sigma Engine	116kW (155bhp)
	2.0 Ford Duratec Engine	149kW (200bhp)
AeroRace	2.0 Ford Zetec Engine	127kW (170bhp)
MegaBusa	1.3 Suzuki Hayabusa Engine	133 kW(178bhp)

Table 2. Westfield Sportscars SE Variants

It has been shown that there are three types of hybrid architectures, series, parallel and combined. This section will discuss the practicality of implementing the different types of hybrid architectures into a Westfield Sportscars racing car.

3.3.1 Series Hybrid Architectures

Miller defines two categories of series hybrid architecture, depending on the size of the energy storage system. If the energy storage system is large, then the vehicle is of the range extender type and can be thought of as an electric vehicle with an auxiliary power unit (range extender ICE) attached to charge the energy storage for extended range vehicle operation. If the energy storage system is small (1-3kWh), then the ICE takes on the role of load following the demand of the vehicle [16], this is known as a load following series hybrid powertrain.

A range extender series hybrid powertrain is designed to provide an electric only range for city use and an extended range with the range extender ICE for extra-urban driving. The extra-urban driving is restricted to the power that the range extender engine can produce, typically a reduced power designed to allow motorway cruising. For motorsport use, a vehicle requires high performance for the duration of a race. Therefore, two distinct modes of operation would not be suitable.

A load following series hybrid powertrain is designed to have a larger ICE and a smaller energy storage which acts as a peak power buffer. In this configuration the ICE can be run at constant higher power as the power required at the road is decoupled from the power required from the range extender. The maximum power of the vehicle is therefore a combination of the maximum power of the ICE and the maximum power of the energy storage device. In theory, this configuration results in the maximum power of the engine becoming the average power of the vehicle. However, there will be efficiency penalties of running an engine at maximum power as well as efficiency penalties in the extra power conversions that are required (from mechanical, to electrical and back to mechanical) in the motors and energy storage devices. There is scope for a load following series hybrid electric vehicle to improve the performance and acceleration of a race car but these efficiency penalties will need to be taken into account.

For this type of series architecture to be used in a Westfield Sportscars racing car, the engine would need to be adapted to take a generator mounted to its output with drive to the wheels provided by an electric drivetrain. Achieving this consistently may be difficult due to the wide range of engines currently used in Westfield Sportscars vehicles.

3.3.2 Parallel and Combined Hybrid Architectures

A Westfield Sportscars racing car has an engine, attached to a manual gearbox, driving a rear mounted differential, driving the rear wheels. Keeping this existing drivetrain, there are three areas within the drivetrain that electric drive could be installed, these are:

- Pre-transmission area
  - This motor position will increase the power transmitted through the clutch to the transmission.
- Post-transmission area
  - This could be onto the input or the output of the differential. The output of the differential also includes in-wheel motors acting on the rear wheels. This motor position will increase the power transmitted through to the rear wheels and will also be able to produce power throughout the gear change events.
- Front transmission area
  - This could be as two motors driving each wheel or one motor acting through a differential. This motor position will be able to provide power to the front wheels, which will increase the overall power and be able to power through the gear change events. It may also allow more power to be transmitted to the road if the engine has reached the limit of traction at the rear wheels. This motor position would also be able to recoup more

regenerative braking energy due to it acting on the front wheels and taking advantage of weight transfer during braking.

An illustration of the vehicle drivetrain, showing the three areas of possible electric drive integration, is shown in Figure 7. By alternating which of these areas are used, it is possible to define seven hybrid electric vehicle sub-architectures. Table 3 shows these and identifies which motor areas are utilised.

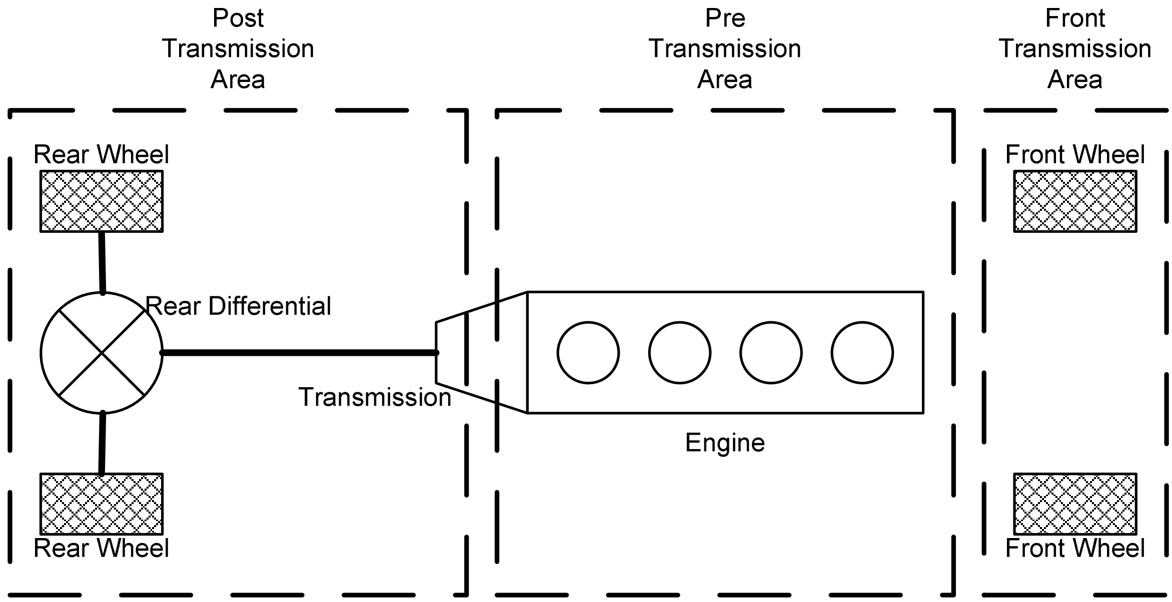


Figure 7. Drivetrain Areas for Motor Integration

Architecture Type	**Sub-Architecture**	**Pre Transmission Area**	**Post Transmission Area**	**Front Transmission Area**
Parallel Hybrid	Basic	Yes	No	No
Parallel Hybrid	Post Transmission	No	Yes	No
Parallel Hybrid	Through-the-road	No	No	Yes
Parallel Hybrid	Four Wheel Drive Post Transmission	No	Yes	Yes
Combined Hybrid	Post Transmission	Yes	Yes	No
Combined Hybrid	Separate Axle	Yes	No	Yes
Combined Hybrid	Four Wheel Drive	Yes	Yes	Yes

Table 3. Possible Hybrid Electric Architectures for a Westfield Sportscars Racing Car

3.4 Electrical Energy Storage Systems

3.4.1 Introduction

There are two types of electrical energy storage systems, ultracapacitor systems and electrochemical systems. Ultracapacitors are large capacitors with very high specific power ratings. Electrochemical systems include battery systems such as nickel metal hydride and lithium ion. All energy storage systems are made up by connecting multiple cells together to form batteries. When multiple cells are used to form a battery, a battery management system is required to ensure correct system operation. The following sections will discuss the different types of electrical energy storage systems and the required functions of a battery management system for motorsport use. As the aim of this doctorate is to develop a hybrid electric vehicle, mechanical energy storage devices will not be discussed.

3.4.2 Ultracapacitor Systems

Ultracapacitor energy storage systems are made up of many ultracapacitors, sometimes referred to as supercapacitors or electric double-layer capacitors (EDLC), connected in series to increase the capacity and voltage of the system, and connected in parallel to increase the capacity of the system. Ultracapacitors operate in a similar way to conventional film capacitors. However, ultracapacitors can achieve a much higher specific energy (energy per kg) than conventional film capacitors and a higher specific power (power per kg) than electrochemical energy storage systems. A Ragone plot (a graphical representation of the specific energy vs. specific power of energy storage systems) of how ultracapacitors compare to electrochemical systems is shown in Figure 8.

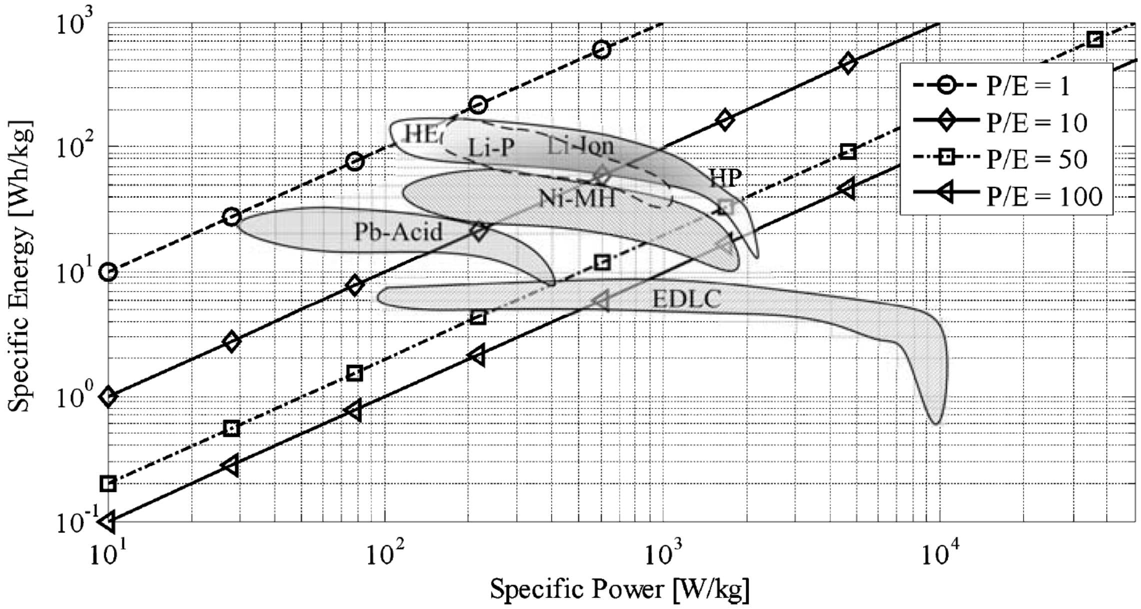


Figure 8. Ragone Plot of Energy Storage Systems [17]

Compared to electrochemical energy storage systems, ultracapacitors have a lower specific energy. For this reason, ultracapacitors are typically used for boost systems where a short boost is required to meet a peak load. This is also made possible by the ability of ultracapacitors to charge at the same high rate that they discharge at.

The disadvantage of ultracapacitors is that the voltage seen at the terminals drops exponentially with state of charge. This is shown in Figure 9 where a 64% drop in state of charge corresponds to a 40% voltage drop at the terminals of the ultracapacitor. Therefore, to maintain a constant power load, the current in the system must increase as the voltage decreases. This can place large demands on power electronics which must then be matched to handle both the maximum voltage of the ultracapacitor system and the maximum current at lower voltages. When the current has increased to the maximum current limit or a minimum voltage limit of the power electronics, then the energy left in the ultracapacitor is unusable and the effective energy of the ultracapacitor will be significantly less than its actual energy capacity.

To compensate for this, DC-DC converters are typically used in ultracapacitor systems to boost the voltage of the ultracapacitor system to within a usable level for the power electronics. However this adds cost, complexity and weight onto an ultracapacitor system. For a system that requires a boost for a short time, this may be deemed acceptable.

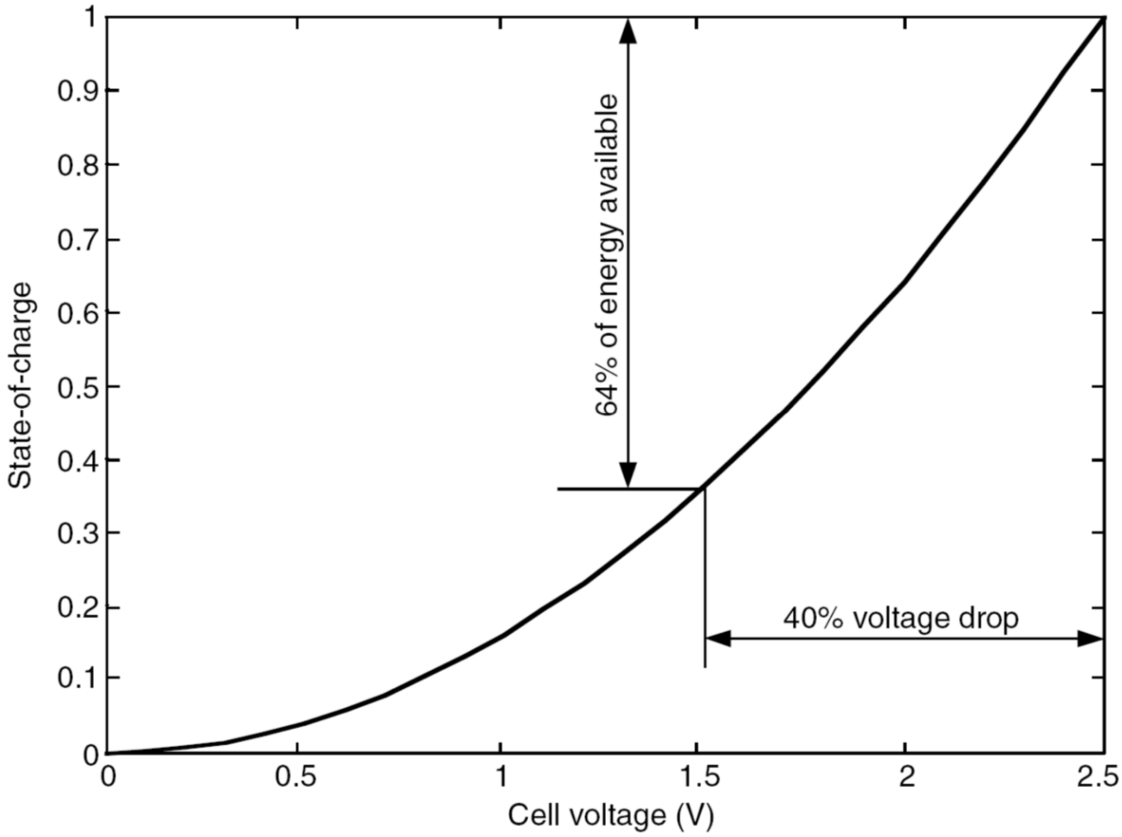


Figure 9. Typical Ultracapacitor State of Charge vs. Cell Voltage [12]

3.4.3 Electrochemical Systems

There have been three main types of electrochemical energy storage systems used in hybrid electric vehicles, lead-acid, nickel metal hydride (NiMH) and lithium ion. Early electrochemical energy storage systems for hybrid and electric vehicles used lead-acid batteries due to their low cost and availability as starting-lighting-ignition batteries in cars [16]. However, their low specific energy (35-50 Wh/kg) means that they are more suitable for stop-start hybrids [18, 19] than for performance enhancing hybrid electric vehicles.

NiMH systems have been widely used in hybrid electric vehicles, an example is the Toyota Prius, which has used NiMH systems since 1997 [2]. NiMH has the advantage of having a higher specific energy (95Wh/kg) than lead acid but the disadvantage of having a very low cell voltage at approximately 1.25V [16]. To reduce the current required for a given power, the voltage of automotive batteries is kept high. With a NiMH system, it may be difficult to reach high battery voltages due to the low voltage of the individual cells.

In comparison, lithium ion cells have a typical nominal voltage of between 3.3 and 3.6V. They also have a higher specific energy (125Wh/kg) than both lead-acid cells and NiMH cells. The specific power of the cells (1500W/kg) is also higher than that of lead acid cells (80W/kg) and NiMH cells (1000W/kg) [16]. For these reasons, lithium ion cells may be more suitable for use in a hybrid electric vehicle for motorsport than other common electrochemical cells. For example, lithium cells have been used in Formula 1 [20].

The major disadvantage of electrochemical systems is that their discharge characteristics are different to their charge characteristics. Typically charging happens at a lower rate than discharging. It is for this reason that small electrochemical systems can be unsuitable for use in systems that require high levels of regenerative braking and might be better suited to applications where the vehicle can be plugged into the grid to recharge the battery system. This becomes less of a problem with larger electrochemical battery systems as the peak charge current that can be handled will be larger.

Furthermore, the performance of lithium ion cells is dependent on their operating and storage conditions. Thermal management is required to allow cold temperature operation and to prevent significant capacity and power fade over time. With no thermal management, the cells are at risk of entering a thermal runaway condition. This occurs when the temperature of the cell rises to such a temperature that exothermic reactions are triggered, causing a catastrophic failure and fire [21]. Thermal management is usually carried out by a battery management system (BMS).

3.4.4 Battery Management Systems

Both an ultracapacitor and electrochemical systems require a battery management system to ensure correct operation of the battery. The BMS protects the cells within the battery against overcharge, over-discharge, short circuits and thermal abuse as well as providing features such as state of charge estimation, state of health monitoring, temperature control, charge discharge power control, cell voltage equalisation and data logging [22].

Cell voltage equalisation is important to ensure that all the cells within a battery are at the same state of charge. If the cells are not at the same state of charge, the cells are at risk of overcharge or over discharge. Cell equalisation can be achieved either through passive or active methods. Passive methods involve switching in resistors to discharge only the cells with the highest state of charge, this usually occurs during or after charging. Active methods involve moving charge from one cell to another by switching inductors or capacitors across cells to act as a temporary energy store [23].

The main objective of cell voltage equalisation is to maintain the capacity of the battery pack as a whole over time by ensuring that all the cells are at a similar state of charge. If the cells are at different states of charge, the effective capacity of the battery pack will be limited by the difference in capacity between the highest charged cell and the lowest charged cell. However, assuming an initially balanced battery, imbalance will only occur over time and over a number of charge/discharge cycles. Therefore, in the case of a racing car where it will be running limited duty cycles and the option of extensive maintenance between races, it may be possible to equalise the cells the cells between races with a maintenance charge and/or external balancing system. The advantages of this would be the dependent on any benefits in weight, reliability and cost.

The most important aspect of a battery management system is its ability to ensure that the battery remains in a safe state at all times. This is important for race cars as, whilst a racing circuit can be considered a controlled environment (when compared to the road), vehicle components are being pushed to their limits and there are increased risks of high speed collisions. The cost of a battery management system can be a significant part of the cost of the battery system and in turn a significant part of the cost of a hybrid or electric vehicle. However, effective implementation of a BMS will extend the life of a battery and reduce the effect of capacity and power fade over time, making the ownership cost of the battery less.

3.4.5 Thermal Management

Batteries and cells are not 100% efficient, which means that when they are used, energy is lost as heat. For high power systems, the heat generated can become significant and requires thermal management. Failure to manage the temperature of a battery can result in accelerated aging, performance degradation and cell failure. Furthermore, for lithium ion cells in particular, it is important to prevent over temperature conditions as they can result in dangerous thermal runaway events [24].

Under high current loads, heat generation is primarily determined by the battery's internal resistance. Internal resistance is a complex parameter, with many different methods of measurement and estimation [25]. For a simple battery with an assumed purely resistive internal resistance, the heat power generated is shown in Equation 1 where P_{batt} is the output power of the battery or cell, I is the current passing through the battery or cell, V_{ocv} is the open circuit voltage of the battery or cell with no load applied and R is the internal resistance of the cell.

$$P_{batt} = IV_{ocv} - I^2R$$
$$P_{heat} = I^2R$$

Equation 1

It can be seen from Equation 1 that the heat power generated is proportional to the square of the current flowing through the battery or cell, making heat generation an issue for high power systems. There are two main methods of thermal management, using air (which works best for cylindrical cells) and using liquid (which works best for prismatic or pouch cells) [26]. Work is also being carried out on the use of phase change materials to aid thermal management of cells and batteries [27].

3.4.6 Energy Storage System Use in Motorsport

The two electrical energy storage systems identified in this section as suitable for use in a hybrid electric vehicle in motorsport are ultracapacitor systems and electrochemical batteries. Of the electrochemical batteries, lithium ion systems have a higher specific energy (energy per kg) and higher specific power (power per kg) when compared to other battery systems. Lithium ion systems also have higher specific energy than ultracapacitors, but a lower specific power.

The result of this is that the operation of a hybrid system will be dependent on the energy storage system used. Due to their higher specific power, ultracapacitors may be better suited to systems that incorporate a power boost for a short amount of time with high levels of regeneration. Lithium ion battery systems do not have the peak power capabilities of ultracapacitors, but can hold a lot more energy and are more suited to applications with limited amount of regeneration. Both ultracapacitor and lithium ion systems require battery management systems to ensure the safety and integrity of the systems.

It is also possible to design hybrid vehicles around mechanical energy storage devices. As the focus of this work is hybrid electric vehicles, mechanical hybrids have not been discussed. However, mechanical hybrid vehicles have been developed for motorsport use and are discussed as appropriate in the literature review.

3.5 Electric Drives

3.5.1 Motors

There is no universally accepted motor type for use in a hybrid electric vehicle. In fact there are five main motor types that can be used. These are brushed DC, brushless DC, induction, permanent magnet synchronous and switched reluctance motors [28]. Each type of motor varies in its mass, torque and power capabilities. This section will review each type and will identify the variations in specification (in terms of power, torque, mass and speed) due to the ways in which these motors are designed and the applications they are designed for.

3.5.1.1 DC Motors

DC motors are an established product and are therefore readily available at a low cost. They are defined by the presence (or absence) of brushes. Brushless DC motors can achieve a higher efficiency and energy density than brushed DC motors and also have the advantage of reduced maintenance issues that are typically associated with brushes.

However, neither type is commonly used in hybrid electric vehicles due to their poor efficiency. They are therefore only occasionally used in low power applications requiring very simple control [28] such as in the Toyota Integrated Motor Assist system, that can start and stop the engine and provide a torque assist, but cannot be used as the main traction power for the vehicle [29].

3.5.1.2 Induction Motors

Induction motors have been used as the traction motor in many hybrid and electric vehicles to date, having advantages over DC motors in terms of controllability, efficiency and power [10, 28]. As a mature and reliable technology, induction motors have been used as traction motors in vehicles such as the GM EV1 and Tesla Sports Car [30].

However, induction motors are typically not as efficient and have a lower maximum speed than comparable permanent magnet motors.

3.5.1.3 Permanent Magnet Motors

Permanent magnet motors, like induction motors, are a popular choice for hybrid electric vehicles due to their higher power density, higher efficiency and more effective distribution on heat.

However there is risk of demagnetisation of the motor at high temperatures [10, 28], reducing the available power of the motor. Permanent magnet motors have been used in many hybrid electric vehicles, including the Toyota Hybrid System [2, 31].

3.5.1.4 Switched Reluctance Motors

Switched reluctance motors have similar power and efficiency qualities to induction motors and are inherently simple machines. As such, they have a high level of fault tolerance and simple control.

However, switched reluctance motors are disadvantaged by torque ripple and can produce electromagnetic interference [10]. Switched reluctance motors have been used as traction motors in the Holden ECOmmodore due to their fault ruggedness and fault tolerant nature [32].

3.5.1.5 Motor Comparisons

Figure 10 shows a comparison of the different types of electric motors; it can be seen that each type has its own advantages and disadvantages. As there is not one obvious front runner, the choice of motor will depend on the requirements of the application. For example, for high performance applications, a permanent magnet motor may suitable due to higher power densities. However, for applications where reliability is required, induction motors and switched reluctance motors may be more suitable.

Propulsion Systems / *Characteristics*	DC	IM	PM	SRM
Power Density	2.5	3.5	5	3.5
Efficiency	2.5	3.5	5	3.5
Controllability	5	5	4	3
Reliability	3	5	4	5
Technological maturity	5	5	4	4
Cost	4	5	3	4
Σ Total	**22**	**27**	**25**	**23**

Figure 10. Comparison of Motor Types [28]

3.5.2 Motor Controllers and Inverters

To drive an electric motor, a motor controller or inverter is required to modify the torque or speed request to the motor. For DC motors, this is usually achieved by a motor controller which reduces the average voltage available to the motor through the use of a chopper circuit [10, 12]. The speed of a DC motor is proportional to its voltage.

For AC motors (induction, permanent magnet and switched reluctance), an inverter is used which converts the DC battery voltage to an AC voltage through the rapid switching of power electronics. For induction motors, torque and speed is usually controlled by variation of the AC frequency (voltage control can be used alongside frequency control to improve low speed operation). For permanent magnet motors, current control is typically used to control motor torque [12].

Feedback to motor controllers and inverters is usually provided by a position sensor which informs the controller/inverter of the rotational position of the motor. This allows the controller/inverter to more accurately control the motor. Failure in this position sensor can cause the drive system to perform poorly [32].

3.5.3 Electric Motor Performance

Electric motors generally have two operating regions, constant torque and constant power. A motor can therefore be defined by the amount of torque that it can produce and the amount of power it can produce. This is typically rated in the amount of torque and power it can produce constantly and the peak torque and power it can produce (before the cooling system of the motor cannot protect it further). This is shown in Figure 11.

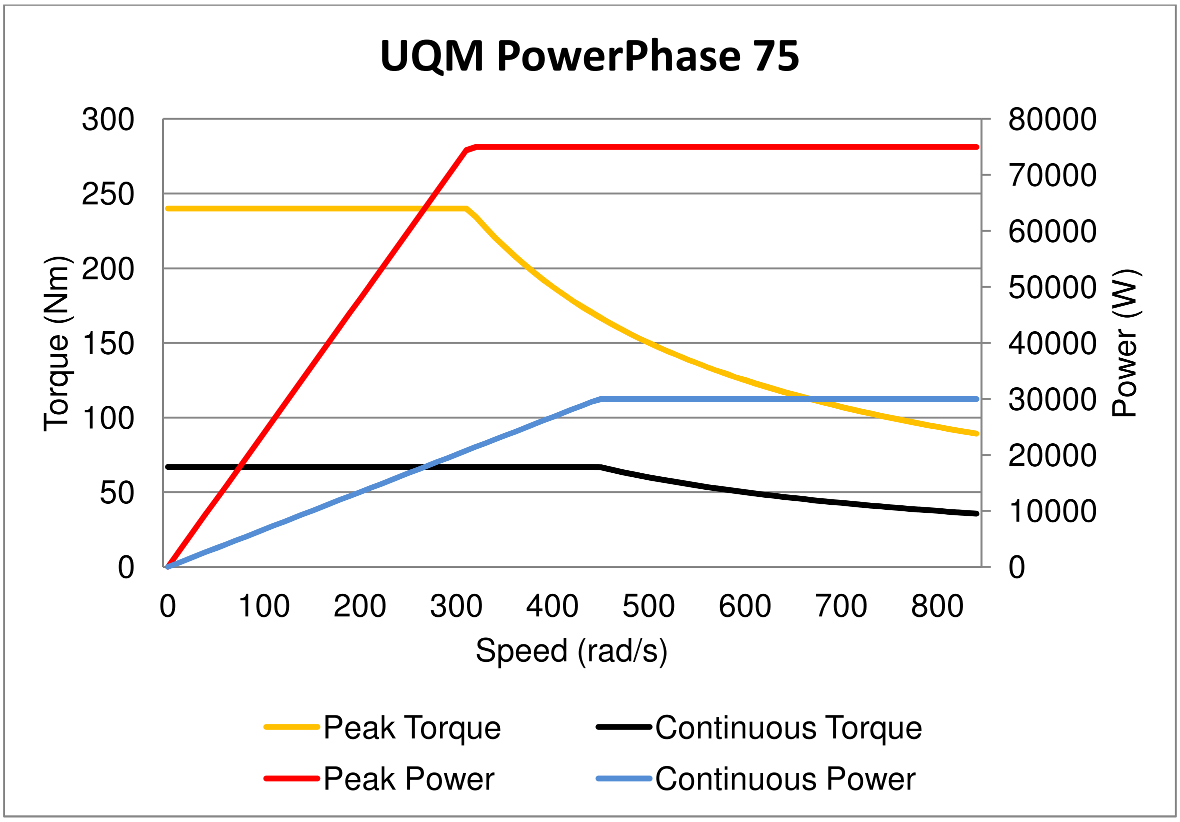


Figure 11. Electric Motor Torque and Power

3.6 Discussion

The literature has shown that the different types of hybrid vehicle can be defined as either series, parallel or combined (series-parallel). Some of the literature also suggests a further hybrid architecture known as complex hybrid architecture typically used to describe architectures that are more difficult to describe. However, it has been shown that through using a conceptual illustration method of describing architectures, exact power flows can be visualised and architectures rigorously defined as either series, parallel or combined. Therefore the complex hybrid architecture does not exist.

Two types of energy storage have been presented, ultracapacitor systems and electrochemical systems. Ultracapacitors have been shown to have a favourable specific power, but their use will be dependent on a system that requires short boosts and little energy storage. Electrochemical batteries have the advantage of storing a larger amount of energy, but cannot match the peak power capabilities of ultracapacitors. Of the three types of electrochemical systems discussed, lithium ion comes closest to the specific power of ultracapacitor systems and therefore may be suitable for use in a hybrid electric racing car. This mix of favourable energy density and power density is why lithium ion batteries have been used in the majority of hybrid electric racing cars to date, including all of the Formula One cars equipped with KERS.

Regardless of the energy storage system type, some form of battery management system will be required to manage the cells that make up the battery. The main function of a BMS used for motorsport will be to ensure the battery is in a safe state and to perform thermal management of the system. This is particularly important for lithium ion systems where overheating and thermal runaway is of particular concern. For motorsport, it may be possible to reduce the complexity of the system, decreasing cost and likelihood of malfunction by performing tasks such as cell voltage equalisation as part of a maintenance cycle.

Five types of motor have been identified for use within hybrid electric vehicles. However, the most appropriate motor type will depend on the exact system requirements. For example, permanent magnet motors may have high power densities, but are expensive compared to DC motors. However, induction motors and switched reluctance motors have high reliability. All of these attributes may be important for a hybrid drivetrain for use in club motorsport dependent on the requirements of the particular system.

3.7 Conclusions

There were many hybrid architectures and hardware options that required consideration for the development of a hybrid electric race car. However it was impossible to conclude at this stage which options would be most appropriate for use in a hybrid electric drivetrain for club motorsport. The final selection was dependent upon further analysis of the success and failures of hybrid electric vehicle technologies when used in other forms of motorsport, the requirements of the customer and the capacity of the system that the drivetrain is to be integrated into.

4 LITERATURE REVIEW

4.1 Introduction

This chapter performs a critical review of the current use of hybrid vehicles in motorsport, identifying: potential to advance their development, potential barriers to implementation of a new hybrid electric drivetrain, and implications that has for Westfield Sportscars.

The competitive nature of motorsport and the drive to gain technological advantages fosters significant innovation within the industry. However, the desire to maintain and grow this competitive edge ensures that this innovative activity is not often published and is guarded by strict confidentiality agreements. The exception to this is student motorsport, where there are not the same commercial implications. This literature review will therefore concentrate on analysing mostly industry data from professional motorsport and mostly published data from academic sources on student motorsport.

The scope of this literature review does not include all of the appropriate literature for this Engineering Doctorate. Where an additional review of the literature is required, outside of hybrid electric vehicle theory and the motorsport industry, this is included in the appropriate chapter.

4.2 Hybrid Electric Vehicle Use in Motorsport

4.2.1 FIA Formula One World Championship

The Fédération Internationale de l'Automobile (FIA) is the world governing body for motorsport and administers the technical and sporting regulations for the Formula One World Championship. In 2007, in line with societal concerns about the environment [1], the FIA announced the introduction of hybrid technology into Formula One from 2009 in the form of Kinetic Energy Recovery Systems (KERS). This move not only made the FIA appear to be more environmentally concerned, but also endeavoured to stem some of the criticism that Formula One had become irrelevant to road vehicle technologies – which were already advancing in this direction [33]. Table 4 shows a breakdown of the technical regulations for KERS in use since the 2011 season.

Maximum Power (In or Out)	60kW for up to 6.67s per lap
Maximum Storage Capacity	400kJ
Maximum Energy Released	400kJ per lap
Control System	Under driver control
Connection Point	Any point in the rear drivetrain before the differential
Hybrid Type	Unrestricted

Table 4. Formula One KERS Regulations, adapted from [34]

The technical regulations only allow the hybrid system to be connected in parallel with the engine, before the differential. This means that Formula One cars equipped with KERS are parallel hybrids. The power flow within a Formula One car with KERS is shown in Figure 12. The restriction on energy storage release per lap means that the hybrid system can only give the car a short boost, which must be under the driver's control.

It is worth noting that in the technical regulations, there are no rules specifying the type of hybrid. Therefore Energy Source 2 and Energy Converter 2, as shown in Figure 12, are not defined. In an electric hybrid, Energy Source 2 would be a battery or capacitor system and Energy Converter 2 would be an electric motor. In a mechanical hybrid, Energy Source 2 could be a flywheel, with Energy Converter 2 a Continuously Variable Transmission (CVT) or similar.

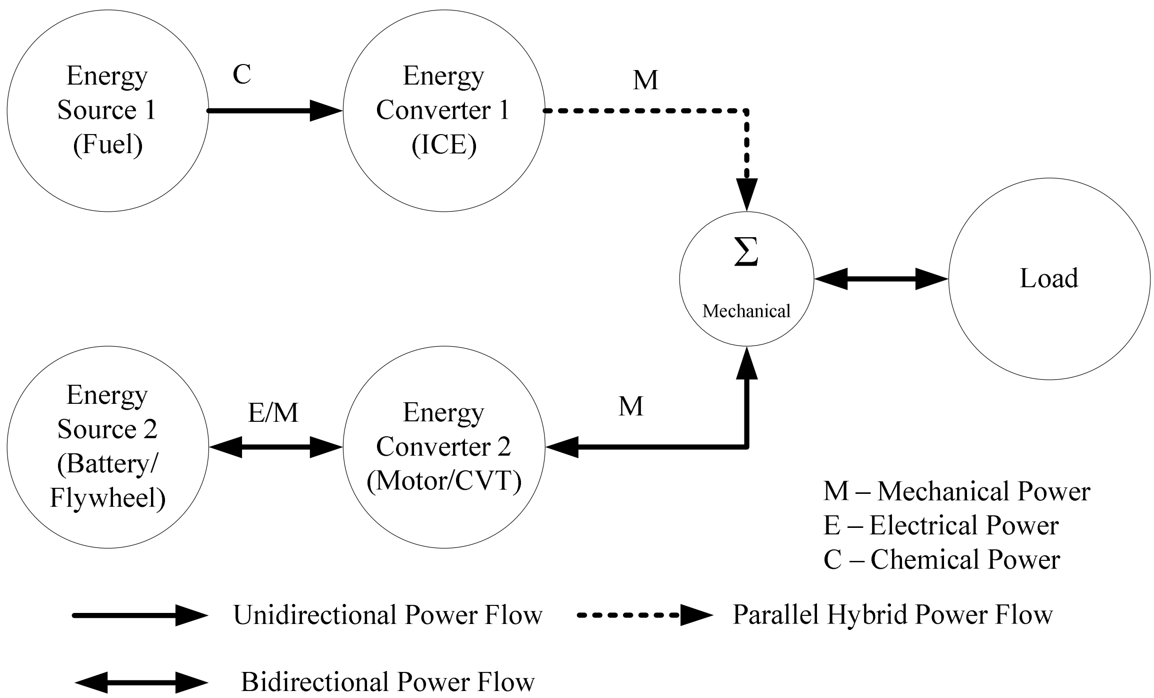


Figure 12. Formula One KERS Power Flow

When the KERS regulations were announced, a number of companies began to design non-electrical hybrid systems for use in Formula One, based on the theoretical higher specific power of a flywheel [12, 16]. For example, Flybrid Systems developed a flywheel based system and Williams Hybrid Power developed an electrical flywheel based system, believing them to have a higher specific power than the batteries in electric hybrid systems.

The Flybrid Systems solution uses a flywheel to store energy and a CVT to convert this rotating mechanical energy to power, which provides a boost to the existing vehicle drivetrain. The developers claim that flywheels offer efficiencies double of that given by electric hybrids, allowing for a smaller and lighter solution [35, 36]. However, little justification is given for the quoted efficiencies, making evaluation of the claims difficult and although the system was primarily designed for Formula One, it was never used on a Formula One car, suggesting that this system does not offer any benefits over an electric KERS system in this application.

The discrepancies in the claimed efficiencies may be due to the comparisons being made for road going systems which must run in limited windows of operation for cost and longevity reasons. However Formula One does not have the same restrictions in cost and longevity and can therefore run systems, for example batteries, outside of their normal operating conditions, creating advantage by pushing this technology to the point where the specific power of a given battery system is greater than that of a flywheel based system.

The Williams Hybrid Power solution uses an electromechanical flywheel to store kinetic energy and an electric machine to convert this kinetic energy to and from mechanical energy from the electrically driven wheels. The rotor of the flywheel has magnetic powder mixed into its composite material. When the rotor is moving, it is able to generate electricity in windings in the stator, which is used to power the electric machine and provide a boost to the existing vehicle drivetrain. This has the benefit of allowing energy to be stored mechanically, but without a direct mechanical drive to the wheels. The drive comes from a separate electric drive that replaces the CVT. This separation of storage and drive allows more flexibility in flywheel location than a convention flywheel based system.

The fact that the Williams Hybrid Power system was never used in Formula One, despite being designed and owned by a Formula One team, is probably for the same reason as the

Flybrid Systems solution has not been used; if cost and longevity are not an option, battery based systems can still have a higher specific power than flywheel based systems. However, the development of the technology in light of the change in Formula One regulations became relevant for road applications as the system has since been used on a Porsche 911 GT3 R Hybrid Endurance sports car [37] and by the Audi R18 e-tron Quattro [38], on which more information can be found in section 4.2.2.

In the 2009 season, only four teams in the Formula One World Championship used KERS. By the end of the season, due to the difficulties in producing reliable KERS systems, only two teams were still using the technology. During the 2010 season, a cost saving agreement was made, through the Formula One Teams' Association, whereby no Formula One teams would implement KERS, although the regulations remained in the rules. With the cost saving agreement abandoned for 2011, KERS was once again used in Formula One, with only three teams deciding to opt out. At this time the theoretical advantages of KERS were known in terms of extra power, reduced lap times and overtaking abilities [39]. However, issues around reliability, weight and cost were not yet fully known or understood. There were also financial implications, with people such as Tony Fernandes, Team Principal at the then Team Lotus team, claiming in 2010 that the costs of implementing KERS cannot be justified when compared to the equivalent spending on wind tunnel testing [40]. It is for these reasons that in 2011, the three new teams in Formula One did not implement KERS.

However, Team Lotus/Caterham implemented KERS in 2012 and Virgin/Maurissia implemented KERS for the 2013 season. The third new team, HRT did not implement KERS before withdrawing from Formula One before the 2013 season. This shows that is between 2010 and 2013, the advantages of KERS must have became more obvious to the teams and now all teams in Formula One run a KERS system. This is shown in Table 5.

Team	Used KERS in			Manufacturer
	2011	2012	2013	
Red Bull Racing	Yes	Yes	Yes	Renault
McLaren	Yes	Yes	Yes	Mercedes
Ferrari	Yes	Yes	Yes	Ferrari
Mercedes	Yes	Yes	Yes	Mercedes
Renault/Lotus	Yes	Yes	Yes	Renault
Sauber	Yes	Yes	Yes	Ferrari
Force India	Yes	Yes	Yes	Mercedes
Toro Rosso	Yes	Yes	Yes	Ferrari
Williams	Yes	Yes	Yes	Williams
Team Lotus/Caterham	No	Yes	Yes	Renault
HRT	No	No	N/A	N/A
Virgin/Maurissia	No	No	Yes	Williams

Table 5. Formula One Teams' Use of KERS

To date, all of the KERS systems that have been used in Formula One have been electric hybrid systems as these have been shown to provide the best performance for the given application (short boosts to aid overtaking) within this industry where cost and longevity are not as relevant as in road applications.

The first example of KERS leading directly to a race win was in the 2009 Belgian Grand Prix where Kimi Raikkonen, driving a KERS enabled Ferrari Formula One car, was able to use KERS to overtake Giancarlo Fisichella in a non-KERS Force India car and keep the lead, despite having a slower overall race pace [41]. This shows that despite the fact that there may be weight distribution penalties by implementing KERS, other advantages, such as boost ability, can result in a more competitive car.

4.2.2 Endurance Racing

The 24 Heures du Mans is the world's most popular endurance race event, held annually in France near the town of Le Mans. Alongside this race, there are a number of other endurance race series, with very similar regulations, such as the American Le Mans Series (ALMS). As the length of these endurance races is significantly longer than in Formula One, the requirements for the races are different and therefore the design of hybrid systems will also be different.

Endurance racing appeared to be taking the lead in hybrid motorsport when in 1993, Chrysler designed a hybrid prototype sports car which consisted of a 559kW AC traction motor, a 373kW electrically coupled flywheel, a 373 kW liquefied natural gas powered turbine and a 9000 µF capacitor bank. The intention of this car was to compete in the 24 Heures du Mans. However, issues surrounding the flywheel containment meant that this car was never raced [42-45]. The failure of this vehicle may explain why there was no further development of hybrid vehicles in endurance racing immediately after this.

In 2009, shortly after the change in Formula One regulations, the sporting regulations for the 24 Heures du Mans introduced provisions for hybrid cars to be able to compete in the race [46]. Whilst no hybrid cars competed in the 24 Heures du Mans in 2009, Zytek did develop a hybrid electric hybrid which competed in the Petit Le Mans stage of the ALMS series, finishing 2nd in the GT1 class and 12th overall [47]. This served to prove the concept that hybrids in endurance racing were now able to compete with conventionally fuelled vehicles.

In October 2010, Porsche raced their 911 GT3 R Hybrid race car in the Petit Le Mans stage of the ALMS series. This vehicle has two 60kW motors driving the front wheels, using energy provided by a Williams Hybrid Power electromechanical flywheel. The car finished 18th out of 41 entries [48]. The power flow around the vehicle is shown in Figure 13, which shows how the ICE and electric flywheel/electric motor interact to form parallel hybrid architecture.

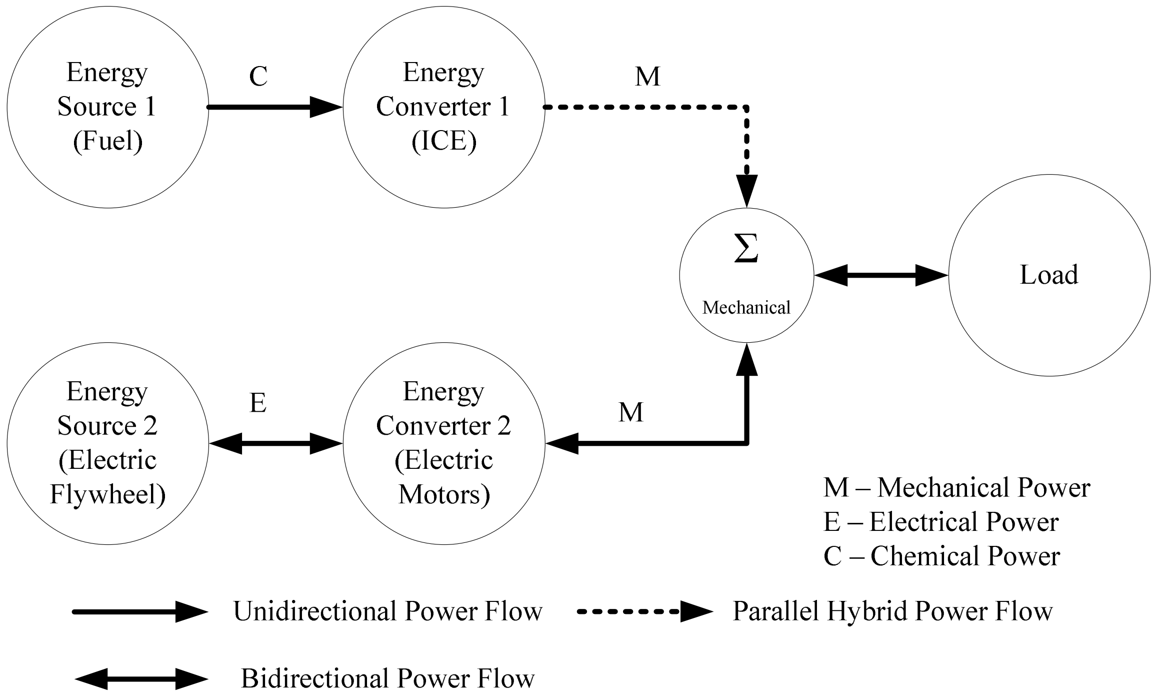


Figure 13. Power flow around the Porsche 911 GT3 R Hybrid race car

In 2011, further sporting regulations for the 24 Heures du Mans were developed to encourage hybrid vehicles to compete. The regulations allow for hybrid systems to reduce fuel consumption and CO2 emissions and dictated that the system must not be aimed at obtaining additional power [49] unlike in Formula One. This indicates that the motivation behind allowing hybrids into the 24 Heures du Mans are primarily environmental and not for performance or competitive reasons. This is explicitly stated in the regulations and is achieved by having the hybrid system not under the control of the driver, meaning that Formula One style push to pass systems are not allowed. This fundamental difference means that the hybrid systems used in Le Mans cars will be significantly different to those used in Formula One. This change is likely to make the hybrid systems designed for Le Mans, closer to hybrid systems designed for road vehicles.

Table 6 shows a breakdown of the regulations for the 24 Heures du Mans relating to hybrid drivetrains. It can be seen that the regulations are less restrictive than those enforced in the Formula One World Championship. The hybrid system is only limited by the amount of energy it can release between two braking events and can be coupled to either the front or the rear wheels. However the system may only be controlled through the accelerator pedal and must also be capable of propelling the vehicle on electric only power along the pit lane (400m) at 60km/h.

Maximum Power (In or Out)	Unrestricted
Maximum Storage Capacity	Unrestricted
Maximum Energy Released	500kJ between 2 braking events
Control System	Accelerator pedal
Connection Point	Either front wheels or rear wheels
Hybrid Type	Electrical or mechanical/electromechanical flywheels – Must be capable of propelling the car along the pit lane (400m) at a speed of 60km/h using only the power generated by the hybrid system

Table 6. 24 Heures du Mans Hybrid Regulations, adapted from [49]

It can be seen that the power and energy capacity of the systems permitted are not restricted and energy release is only restricted between two braking events and not on a per lap basis, as in Formula One. The regulations specify that the system must connect at either the front or rear axles, with the aim of recovering energy from the brakes, therefore any systems developed will be a parallel hybrid. The power flow allowed in the system is therefore identical to that shown in Figure 12 for the Formula One KERS power flow.

Peugeot indicated that they would be entering the 24 Heures du Mans with a diesel electric hybrid drivetrain in 2011. However this car was later withdrawn from the competition due to technical difficulties. MIK Corse developed a car with an electric hybrid drivetrain and successfully tested this vehicle in the Le Mans Series and the 24 Heures du Mans test day. However this car was also withdrawn from the 24 Heures du Mans competition due to technical difficulties [50]. The only car to be entered into the 2011 24 Heures du Mans competition as a hybrid was the Oreca Swiss Hy Tech-Hybrid. This is the first time that a hybrid car has competed in the 24 Heures du Mans. The car has a flywheel based mechanical hybrid drivetrain from Flybrid Systems, originally designed for the Formula One World Championship. The car completed 115 laps before it retired with electrical problems, finishing in 49th position of 56 cars competing.

By 2011, the regulations had been available for three consecutive years, with four teams attempting to build hybrid cars. However, none of these had managed to successfully finish the 24 Heures du Mans. This demonstrates the difficulty in developing a competitive hybrid race car, even for teams with the resources of Peugeot and Porsche.

In comparison to the Formula One World Championship regulations, the 24 Heures du Mans regulations allow for more freedom in the design of the system. It may be that this freedom, whilst allowing the teams to make their own decisions on the design of the system, also makes it more difficult to develop a reliable hybrid system. However it is also true that the budgets for endurance racing teams are significantly lower than that of Formula One teams and that the teams competing in the 24 Heures du Mans and ALMS championships do not have the resources or the budget required to develop hybrid drivetrains to the same standard as Formula One.

In 2012, two teams entered the 24 Heures du Mans race with hybrid vehicles. Toyota competed with two petrol/electric hybrid vehicles with the hybrid system providing additional electric power to the rear wheels. Audi competed with two diesel hybrid vehicles, utilising the hybrid electric flywheel system from Williams Hybrid Power, with electric motors acting on the front wheel. While the Toyota cars both failed to finish the race, the Audi cars finished in 1st and 2nd [51]. This has shown that if sufficient resources are available, it is possible to develop, compete and win in Le Mans with a hybrid vehicle.

One of the drivers of the Audi R18 e-tron Quattro, Alan McNish has been quoted as saying that one of the major advantaged of the Audi system is that it allows the vehicle to behave as if it has traction control [52], otherwise not permitted in the regulations. What this demonstrates is that some of the advantage of having a hybrid system comes not from the reduction in fuel usage, but from the ability to tune the system to behave like traction control.

4.2.3 Formula Hybrid

Since 2007, the Formula Hybrid competition has encouraged teams of university students to design hybrid race cars, based on Formula SAE chassis. Run by Dartmouth College, the purpose of the event is to promote and develop high efficiency hybrid electric drivetrains. Table 7 shows a breakdown of the regulations for the Formula Hybrid competition. It can be seen that the regulations are less restrictive than those for the Formula One World Championship and the 24 Heures du Mans endurance race. The maximum energy storage allowed is larger than other series at 16MJ. All other regulations are open. This is to allow innovation in the development of the drivetrains but also has the advantage that many different types of hybrid drivetrain can be analysed against each other.

Maximum Power (In or Out)	Unrestricted
Maximum Storage Capacity	16MJ
Maximum Energy Released	Unrestricted
Control System	Unrestricted
Connection Point	Unrestricted
Hybrid Type	Unrestricted – Must be capable of propelling the car 75 metres in less than 10 seconds or be determined a hybrid by the judges

Table 7. Formula Hybrid Regulations, adapted from [53]

The regulations for the Formula Hybrid competition allow for any type of hybrid architecture, in contrast to Formula One and the 24 Heures du Mans which only allow parallel hybrids. This freedom allows for, and was designed to allow, many different types of hybrid electric vehicle to be built and competed against each other. This is significant because it allows for the comparison of many different types of hybrid drivetrain to be raced against each other. Overtime, it may be possible to identify which drivetrain is most suited to motorsport.

The Thayer School of Engineering competed in the first Formula Hybrid event in 2007 with a series hybrid drivetrain that was designed a year earlier than the start of the competition [54]. It was this vehicle that the concept for the competition was formed around. However, this vehicle failed to finish the event in 2007. This shows the high degree of risk involved with designing these hybrid electric vehicles as the vehicle that the competition was based on, that had been working two years before the competition, failed to compete in all events at the first Formula Hybrid event.

The Illinois Institute of Technology entered two cars into the Formula Hybrid competition in 2008, one being a parallel hybrid and the other being a series hybrid [55, 56]. In the competition, the parallel hybrid was able to compete in two dynamic events, the series hybrid failed to compete in any dynamic events. This could suggest that a parallel hybrid system is more reliable than a series hybrid. However more evidence would be required to determine whether a particular type of hybrid is more likely to finish the events than any other type.

The University of Guelph designed a car concept in 2008 with a complex hybrid architecture [57]. The car consisted of a genset (an internal combustion diesel engine and a generator), mechanically coupled to the road through a CVT and electrically coupled to a battery system. The generator is attached directly to the engine (with a fixed ratio), with the engine driving the rear wheels through the CVT. An electric motor drives the front wheels through a differential. The power flow within the system is shown in Figure 14, where it can be seen that there are two energy converters and two energy sources.

The University of Guelph design was not raced in the Formula Hybrid competition. Initial analysis found that the power of the diesel engine was too low to provide acceptable acceleration and maximum velocity. It is also likely that if this car was built, that the complex nature of the drivetrain may have introduced reliability issues, for example, in the control of CVT and the engine to enable both torque to be transferred to the road and keep the energy storage system charged to allow the front wheels to be driven by the electric motor.

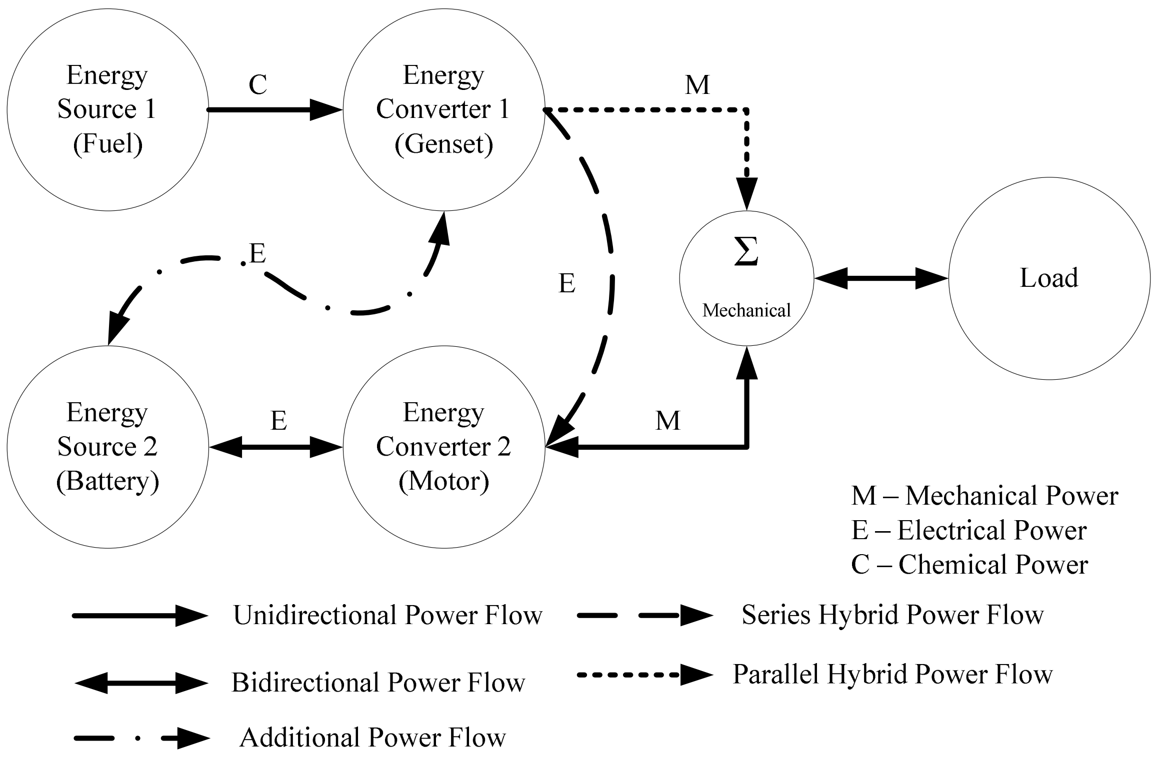


Figure 14. University of Guelph Formula Hybrid Power Flow

In the five years that Formula Hybrid has been operating, there have been a total of 143 entrants. Table 8 shows how the number of entrants has changed as the competition has developed along with the number of entrants that have completed all of the dynamic events. It can be seen that the number of entrants has increased each year (with a drop in

2012). The largest number of finishers was seen in 2010. As 2010 had a high number of entrants and finishers, it is a good year on which to base analysis on different hybrid electric drivetrain types.

Year	Entrants	Finishers
2012	25	6
2011	33	1
2010	30	12
2009	30	6
2008	16	3
2007	9	3

Table 8. Formula Hybrid Entrants

Formula Hybrid (as well as Formula SAE and Formula Student) differs to other motorsport events in that the scores that the teams receive are based on points earned over a number of different events. These events range from static events, such as design judging, to dynamic events, such as an endurance race of 22 km. The points awarded for each event are shown in Table 9. This differs from club motorsport where there are no static judging events, only the races. For that reason, only the dynamic event results are relevant to comparisons with club motorsport and therefore the static event marks will be ignored.

Event	Points	Type
Design	200	Static
Presentation	100	Static
Acceleration – Electric Only	75	Dynamic
Acceleration - Unrestricted	75	Dynamic
Autocross	150	Dynamic
Endurance	400	Dynamic

Table 9. Formula Hybrid Events and Points Available

As there were a comparatively large number of finishers, the results of the 2010 competition can be used to investigate if there is a particular hybrid architecture that does better in the competition. Of the twelve finishers, four were series hybrids and eight parallel hybrids. The average dynamic event score for the competition was 340. The average score for the series hybrids was 216, with an average score of 402 for the parallel hybrids. This indicates that parallel hybrids performed better on average at the dynamic events. This is most likely due to the fact that all of the maximum torque possible is going to the wheels from the onboard energy converters in a parallel hybrid (both engine and motor), whereas for a series hybrid, only the electric traction motor(s) provide tractive effort to the wheels.

It is possible to analyse the drivetrains of the cars that took part in the Formula Hybrid 2010 competition to identify any patterns in the cars that scored higher than other cars. A method of comparing the drivetrains in the Formula Hybrid cars is to look at the hybridisation factors of the parallel hybrid vehicles. The hybridisation factor (HF) of a parallel hybrid is defined as the power of the electrical machine(s) divided by the total power of the vehicle [58], as shown in Equation 2.

$$HF = \frac{P_{EM}}{(P_{EM} + P_{ICE})}$$

Equation 2

The hybridisation factor is an accepted measure of vehicle hybridisation, used throughout the literature. For road vehicles, Lukic and Emadi look at the fuel economy and dynamic performance of hybrid vehicles with varying HF. It was suggested that a HF of between 0.3 and 0.5 gave the optimal level of hybridisation, in terms of fuel economy and performance [58]. However, this study was based on road vehicles with optimum being defined by the vehicles ability to meet a range of targets, such as 0 to 26.8ms^{-1} (0-60mph) acceleration times of 12 seconds, fuel economy minimisation over road drive cycles, vehicle gradeability targets (the highest grade a vehicle can ascend at a given velocity) and being able to be charge sustaining. While the minimisation of vehicle acceleration times is relevant to racing cars, times far below 12 seconds would be expected. Other targets, such as gradeability, charge sustainability are not directly relevant to racing cars and so the suggested optimum level of between 0.3 and 0.5 is unlikely to be true for race cars.

In a similar study, Holder and Gover found that a HF of between 0.49 and 0.60 gave the optimal level of hybridisation in terms of fuel economy and performance [59]. This study concentrated on fuel economy to determine the optimum level. Similar to the study carried out by Lukic and Emadi [58], while 0-60mph acceleration time and vehicle gradeability was calculated for each vehicle, it was not used as the primary method of determining the optimum level of HF and therefore has little relevance to race cars.

To investigate the effect of varying HF on racing cars, the HF of all of the parallel hybrid cars that finished the 2010 Formula Hybrid competition are shown in Figure 15. The range of HF is between 0.38 and 0.69. It can be seen that there is a positive relationship between hybridisation factor and the total points scored in dynamic event. The cars with a higher HF received a higher dynamic event point score than those with a lower HF. Therefore, based on the results from the 2010 Formula Hybrid competition, the most successful cars are parallel hybrids with a high HF. From the limited results, there does not appear to be a point at which a high HF reduces the competitiveness of the Formula Hybrid racing cars.

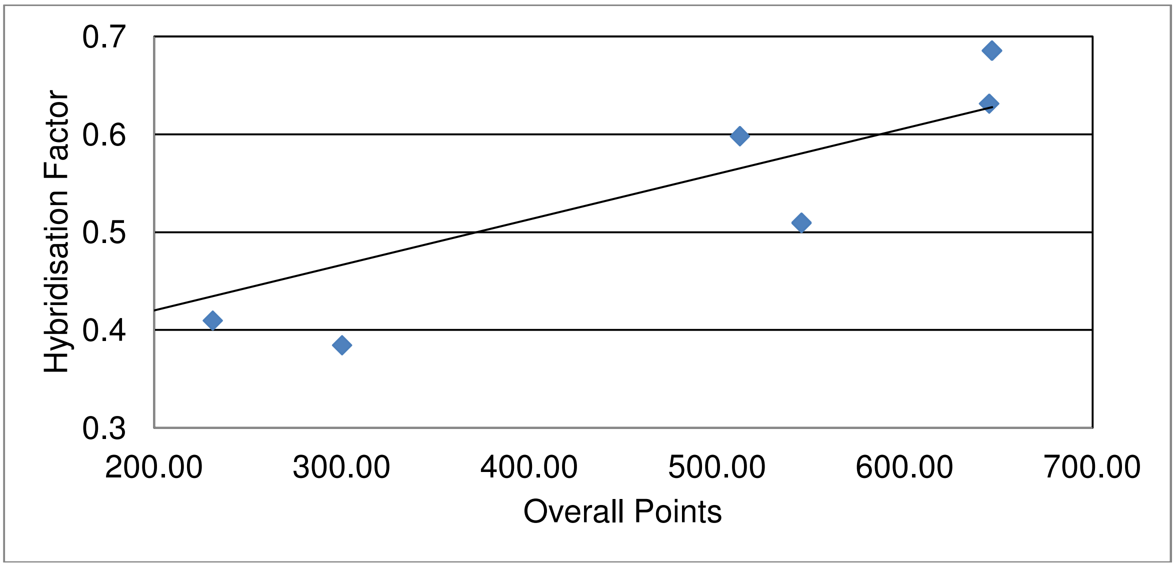


Figure 15. 2010 Formula Hybrid Parallel Hybrid Results against Hybridisation Factor

Of the 30 entrants in Formula Hybrid in 2010, 16 were series and 14 were parallel. As 12 vehicles finished, that means that 18 vehicles did not finish. Out of the 18 non finishers in 2010, 12 of the series hybrids failed to finish and 6 of the parallel hybrids failed to finish the event. Using a total population of 143 vehicles to have competed in Formula Hybrid, and a confidence level of 95%, 43% ±24% of the parallel hybrids failed to finish all of the events and 75% ±22% of the series hybrids failed to finish all of the events. Due to the large margin of error, the results of this small analysis cannot be said to be statistically significant. However, it does suggest that parallel hybrids are more competitive than series hybrids in the Formula Hybrid event. This may be due to series hybrids being unreliable compared to parallel hybrids (with parallel hybrids there is going to be a degree of redundancy) or it may be due to the fact that it is easier to convert an existing Formula SAE conventionally fuelled vehicle into a parallel hybrid than into a series hybrid.

Gordon Kirby, a member of the Formula Hybrid judging committee, discusses the Formula Hybrid competition on his blog. In one entry to the blog, Rob Wills, chair of the Formula Hybrid electric rules committee, discusses the rules of Formula Hybrid and suggests that while the regulations are designed to allow as much freedom and innovation in the development of hybrid electric racing cars, teams are still constrained by the rules of the competition. In particular, vehicle designs are tailored to maximise the points available in the competition across the different events [60].

From this it can be seen that even Formula Hybrid, whose regulations have been designed to be as free and technically open as possible, struggle to maximise innovation in the development of hybrid electric racing cars. Therefore, while Formula Hybrid provides a good opportunity for innovation in the development of hybrid electric racing cars, there is scope for more innovation, particularly within a less restrictive format.

4.2.4 Formula Student Class 1A

As a response to the growing Formula Hybrid competition, in 2009 new regulations for Formula Student were introduced which allowed low carbon vehicles to compete in the newly formed Class 1A. The vehicles entered into Formula Student Class 1A are a mix of hybrid, electric and alternatively fuelled ICE vehicles. Table 10 shows the number of entrants and finishers from previous Formula Student Class 1A competitions. Whilst it can be seen that the number of competitors in the Formula Student Class 1A event is increasing each year, similar to the first Formula Hybrid events, only a small number have competed and not many of these cars have finished all of the events. Furthermore, hybrid electric vehicles only make up a small number of these vehicles. Therefore, there is not sufficient data from which to draw conclusions. Once the event has become more established, there may be more entrants and finishers, allowing analysis of the results.

Year	Entrants	Finishers
2012	10	3
2011	16	3
2010	9	2
2009	5	3

Table 10. Formula Student Class 1A Entrants

4.2.5 Club Motorsport

Whilst there have been no examples of hybrid vehicles competing in club motorsport, there are examples of electric vehicles. The highest profile example of electric cars in club motorsport is the EV Cup electric race series, which includes former British Government Minister of Science Lord Paul Drayson as a competitor [61]. The EV Cup competition was due to start in 2011, but did not start due to a lack of vehicles to race with. This shows that despite electric cars potentially being simpler than hybrid electric vehicles, due to only having one energy converter, developing electric racing cars is a difficult and costly task and could explain why the limited examples of successful hybrid electric racing cars have been in very well funded series such as Formula One and Le Mans.

Another example of an electric club motorsport event is the Formulec EF01 Electric Formula 3 racing car, produced by French firm Segula Matra Technologies, who were planning a ten event electric racing championship to start in 2012 [62]. The team behind the car were then given the opportunity to be the sole supplier for the FIA Formula E series, an all electric race series and the plans for the race series were abandoned [63]. However, with costs of competing in the British Formula 3 championship around £680,000 ($800,000) [64], and the cost of being involved in an electric version likely to be higher. This means that while the Formula E championship is too costly to be considered club motorsport, it has a good chance of being successful if it can find teams with the required financial resources.

The main way in which club motorsport differs from professional motorsport is that the drivers are usually the owners of the car and are competing for the enjoyment gained from racing and not primarily for commercial benefit. Yamakoshi et al. have found that during racing the heart rate of drivers increases to approximately 150 beats per minute, with lower blood pressure and higher ear drum temperature immediately after racing than at rest [65]. It is suggested that these changes will be more significant at higher levels of lateral and longitudinal acceleration.

Similarly, Backman found that the heart rate of racing drivers rose to 74% of an individual's maximum possible heart rate during racing [66]. It was found that compared to other similar activities that raised heart rates to similar levels, such as rowing, motor racing puts a larger strain on the neuromuscular system. The reason for this was attributed to the high levels of lateral and longitudinal acceleration that a racing driver is put under during racing.

Therefore, if the enjoyment that drivers get from club motorsport it related to the lateral and longitudinal acceleration that they are subjected to, these accelerations should be maximised. One method of increasing lateral acceleration is through the use of aerodynamic devices; however the development costs for developing aerodynamic solutions is too high for club motorsport manufacturers. The typical way for club motorsport vehicles to increase lateral acceleration is through suspension setup and decreases in vehicle mass. It has been shown that hybrid electric drivetrains have the ability to increase longitudinal acceleration. Therefore, to make sure that lateral acceleration is not decreased, decreasing the enjoyment that the driver receives, the mass of a hybrid system for club motorsport must be kept to a minimum.

While club motorsport does not have the same links to the large automotive companies as professional motorsport, it is closely linked to the UK's large number of niche vehicle manufacturers. Not only do many of these companies rely on club motorsport to provide sales of racing cars and advertise their road vehicles, but it is also used as a medium to test and develop their road vehicles. It is important that, to meet any future government regulations for road vehicle emissions, any alternative drivetrain solutions for this industry are proved on the racing track. Therefore, the development of alternative drivetrains for this sector of the industry is likely to increase in importance.

4.3 Importance of Motorsport

Like every large industry, the motorsport industry is under pressure to invest in environmentally friendly technologies. While the adoption of hybrid electric vehicle technology may not be required for racing purposes, it may help prevent motorsport from becoming irrelevant and ultimately damaging the companies that are involved in this industry and therefore the UK economy. Motorsport is important to the UK economy for two main reasons, the contribution of the motorsport industry through the companies that reside in Motorsport Valley and the transfer of technology to the wider global automotive industry.

4.3.1 Motorsport Valley

Motorsport Valley describes the regions, within a radius of approximately 50 miles of Oxford, in which there are around 2,400 companies that are involved in the motorsport industry. These companies contribute an estimated £5 billion worth of sales to the UK economy and provide approximately 40,000 jobs [67]. The majority of the world's racing cars are designed and manufactured in Motorsport Valley [68].

These companies range from large multinational corporations to small and medium sized independently owned British firms. This mix of companies has created a framework of relationships based on interdependency and cooperation alongside fierce competition. This has resulted in the creation of a powerful knowledge community that is able to generate and disseminate knowledge throughout the competing companies through both social and business interactions [68-70].

Due to the size and importance of this industry, it is therefore important that attempts are made to protect it. While motorsport is unlikely to have direct pressures to become more environmentally friendly, it is possible that external pressures, such as sponsorship, will become significant. The unique make up of Motorsport Valley also lends itself well to developing innovative ways of resolving the issues of environmentally friendly motorsport and potentially transferring this knowledge to the wider automotive industry. This means that it is the ideal industry in which innovative new ideas around hybrid electric racing cars can be developed.

4.3.2 Technology Transfer

Traditionally motorsport was used as a proving ground for automotive manufacturers as well as a way of maximising marketing opportunities. Therefore technological innovation developed on the track provided a societal benefit by being beneficial to road cars, usually in terms of safety or refinement. Examples of this are modern disc brakes, turbo charging, tyre technologies and aerodynamics. However, as race car technology has matured, the amount of new ideas with application to road cars has lessened [71].

It has been argued that, for the motorsport industry to survive as a sport in the current worldwide economic recession and given the current climate of environmental lobbying, that motorsport must renew the link between motorsport and technology transfer to road vehicles [72]. Through this, small manufacturers, with innovative ideas, may be given the opportunity to promote their low CO_2 technologies on a global scale [73].

Therefore, the introduction of environmentally friendly technology, such as hybrid electric vehicle technology into motorsport could not only benefit the motorsport industry, but may have wider impacts on the wider global automotive industry. An example of this, developed outside of Motorsport Valley, is the Ferrari 599 GTB Fiorano Hy-KERS, a high performance sports cars that uses hybrid electric vehicle technology derived from the Formula One KERS systems [74]. For a company like Westfield Sportscars, development into hybrid electric vehicle technology in motorsport could see similar transfer to road vehicles, providing the possibility of additional income streams as well as boosting the company's environmental credentials.

4.4 Summary of Key Points

The first major instances of hybrid electric vehicle use in modern motorsport was seen in 2007, when it was announced that teams participating in Formula One would be able to use Kinetic Energy Recovery Systems (KERS) from the 2009 season. This was an attempt to promote innovation in hybrid race car technology with the potential for this technology to be transferred to road vehicles [75]. Also in 2007, the first Formula Hybrid Competition, organised by Dartmouth College and the Society of Automotive Engineers (SAE), took place, encouraging university students to develop hybrid electric race cars based on a Formula SAE chassis [56]. From 2011, hybrid electric vehicles were permitted to race in the 24 Heures du Mans endurance race, following the running of a number of prototype hybrid electric vehicles in the American Le Mans Series (ALMS) in 2009 [76], leading to a hybrid vehicle winning the 24 Heures du Mans in 2012.

Whilst these race series' have provided an opportunity for innovation in the field of hybrid electric vehicles in motorsport, the systems that have been developed for each race series are vastly different from each other in terms of performance and system operation. This is due to the fact that the design of each system is primarily led by the different regulations for each series. Formula One has a boost system that aids overtaking and acceleration, with teams currently favouring electrical hybrid systems over mechanical hybrid systems. Le Mans, being an endurance race, is designed to see fuel saving systems, eliminating the needs for pit stops. Formula Hybrid cars generally have lower powered systems due to the limited packaging space within the Formula SAE chassis regulations.

This means that each system is effectively designed by the governing body that sets the regulations. Each team or competitor is then left to implement their interpretation of the system that the governing body had in mind. By restricting the scope of each system, development costs can be reduced; cars can be kept competitive with each other whilst maintaining the use of cutting edge technology. However, these restrictions on design can restrict innovation and therefore restrict the benefits hybrid electric vehicles could bring to motorsport. These benefits include the potential for performance increase, CO_2 emissions reduction and the potential to make motorsport more relevant to road car technology. At present it is argued that the motorsport industry, which generates approximately £5 billion of sales in the UK each year [67], is at risk of becoming irrelevant if the technology transfer link from motorsport to road going vehicles is not preserved [72].

In contrast to all of the current examples of hybrid electric vehicle technology in motorsport, where the regulations are set by the governing body and it is the responsibility of the individual teams to then develop the technology solutions, club motorsport introduces a new aspect to hybrid electric race car development as the vehicle specifications for a race series can be set by the vehicle manufacturer. Club motorsport is a low cost form of motorsport, consisting of low cost racing cars typically raced by amateur drivers who own and maintain their own vehicles.

4.5 Conclusions

Within club motorsport, there is the potential to allow the vehicle manufacturer to design appropriate hybrid vehicle technology for racing prior to regulations being agreed. For this engineering doctorate, club motorsport therefore presented an opportunity to advance the development of hybrid electric vehicles in motorsport in general by developing a drivetrain for a performance hybrid electric vehicle without the constraint of pre-determined race regulations as well as proving an opportunity to develop and test hybrid electric vehicle technology that is relevant and accessible by the UK's niche vehicle manufactures. Westfield Sportscars and Potenza Technology were ideally placed to take advantage of this situation by developing an innovative hybrid drivetrain suitable for use in club motorsport.

However, the companies that compete in the club motorsport sector do not have the large budgets to develop drivetrains because of the need to keep costs to a minimum for owner drivers. To advance the development of hybrid electric vehicles in motorsport, it will be important to overcome the barriers of cost and complexity. Therefore, part of the innovation in developing a hybrid drivetrain for club motorsport will be in keeping the costs to a minimum.

Innovation at this level may then lead the way in transferring performance based hybrid electric vehicle technology to niche vehicle applications, where there is likely to be a future need for manufacturers to be seen to be developing environmentally friendly solutions.

This literature review shows that there is no single system that is suitable for all possible applications. The technology that is successful depends heavily on the requirements of customer and industry, e.g. Formula One's regulations which restrict technology to use for short bursts of energy versus Le Mans' regulations which restrict use to fuel economy benefits. There is also significance in the availability of resources, for example in Formula one, a lower reliance on cost and longevity means that electrical systems can be exploited and therefore favoured over other alternative drivetrains, such as mechanical flywheels.

The nature of the Formula Student competition has allowed a comparison of different technologies with similar applications and this has shown that parallel hybrids perform better in this form of motorsport and that the higher the hybridisation factor the better the performance of a vehicle.

The literature review has shown that club motorsport presents a unique opportunity within the motorsport industry to develop an innovative hybrid electric drivetrain. There are currently no predetermined regulations for hybrid electric vehicle racing in club motorsport and as such, the design of the system can be completely determined by the manufacturer and not the governing body. This presents a significant opportunity for innovation that has the potential to have a wider impact on the motorsport industry.

Furthermore, no attempts have been made to develop a hybrid electric drivetrain for use in club motorsport, in which there exists a large number of companies competing. The development of a common hybrid drivetrain that could be used by these niche vehicle companies would introduce a technology transfer link between motorsport and road going vehicles.

However the technology decisions for this doctorate will still depend on the requirements of application. To be considered innovative, a new hybrid electric drivetrain would need to meet the particular cost, complexity and reliability requirements of the club motorsport industry. Therefore it is important that the requirements of the customer, the industry and the supporting company are fully understood prior to drivetrain design.

5 REQUIREMENTS ANALYSIS

5.1 Introduction

Having identified that there is scope for introducing hybrid vehicles into club motorsport, an investigation into the requirements of such a system was necessary. Four stakeholders to the system were identified, each having their own requirements. The four stakeholders were:

- The supporting company, Potenza Technology
- The Motorsport Association (MSA), responsible for setting the regulations governing motorsport in the UK
- The Vehicle Certification Agency, responsible for registering vehicles for use on the highway
- The potential customer.

The aim of this chapter is to identify and understand the requirements of the supporting company, the motorsport regulations and road regulations. The customer requirements are investigated in chapter 6 and chapter 7.

The requirements analysis was originally carried out in 2007, at the start of the project. However, since this time there have been changes to some of the requirements, the motorsport and road requirements in particular. Any changes in requirements are shown at the end of each section.

The scope of this chapter does not include the feasibility of meeting any particular requirements or identifying technical challenges or solutions in meeting these requirements. These are investigated in later chapters.

5.2 Company Requirements

To identify the requirements of Potenza Technology, the supporting company for this Engineering Doctorate, an interview was carried out with the Managing Director, Dr. Paul Faithfull. Dr. Faithfull is also the Managing Director of GTM Sports Cars and Technical Director of Potenza Sports Cars and Westfield Sports Cars. Potenza Technology is the sole provider of engineering services to Westfield Sportscars. The interview was carried on the 27th of April 2007, with the objectives to determine the following requirements from the point of view of Potenza Technology. More information on the interview can be found in Submission 2 of this Engineering Doctorate [5].

Dr. Faithfull was used to determine the company requirements as he is best placed to determine the outcomes that Potenza Technology would like to see from this work, as well as having an in depth knowledge of the niche vehicle industry in the UK. However, the results of the interview were taken as a starting point for the system requirements where later work contradicted these results.

The results of the interview are shown in Table 11. Requirements were classified as either a 'Must Have' or an 'Aim'. A 'Must Have' requirement is one that must be implemented in the system. An 'Aim' type of requirement is one that the company would like to see implemented, but is not system critical.

Requirement	**Type**
Work with all cars Potenza Sports Cars sell	Aim
Work with Westfield Sportscars SE models	Must Have
Can be retro-fitted to old Westfield Sportscars SE models	Aim
Is an electric hybrid	Must Have
Uses the same parts as the electric vehicle currently being developed	Aim
Driver remains in control of the vehicle and the hybrid system	Must Have
Can be used on the race track	Must Have
Can be used on the road	Aim
Increases vehicle acceleration	Must Have
Westfield Sportscars SE to achieve 0 to 26.8ms^{-1} (0-60mph) in 3 seconds	Aim
Hybrid system allows optional extras, such as boost or ABS.	Aim
System must be safe	Must Have
Parts are not user serviceable	Must Have
All components are sealed to protect users from accessing internals	Must Have
Retail price below £8,000	Aim
Unit cost of £4,500	Aim

Table 11. Company Requirements

Looking at the 'Need' requirements, it can be seen that the main company objective is to develop an electric hybrid drivetrain, designed for the track, and used in the Westfield Sportscars SE model. The system must be safe and must increase the acceleration of the vehicle. Although the maximum system price was identified by the company as £8,000, this was further investigated in the customer requirements and was therefore used only as a guide at this stage.

5.2.1 Changes in Requirements

Since the start of this Engineering Doctorate, Potenza Technology designed the Westfield Sport Turbo, a variant of the Westfield SE with a 1600cc turbocharged petrol engine. The chassis is based on the SE chassis, but with some strengthening modifications. The majority of cars now sold by Westfield Sportscars are Sport Turbos. Therefore Potenza Technology requested a hybrid drivetrain to be based on a Westfield Sportscars Sport Turbo, shown in Figure 16.

Figure 16. Westfield Sportscars Sport Turbo

5.3 Motorsport and Road Requirements

The MSA Competitor's Yearbook, also known as the 'Blue Book', details all of the regulations that club motorsport vehicles must adhere to in order to be eligible to race in a UK based club motorsport event. In addition, there are specific regulations set by each series organiser that aim to keep the performance of the competing vehicles at a similar level. This typically covers drivetrain systems, tyres and chassis modifications in consultation with the manufacturer.

Through an analysis of the regulations held within the ‘Blue Book’, it was found that the only regulation applicable to a hybrid electric drivetrain was the need to retain a conventional braking system.

For the road requirements, Westfield Sportscars currently has European Community Small Series Type Approval for the Sport Turbo Model. This allows Westfield Sportscars to sell up to 1000 cars per year, in any country in Europe, without the need for testing each vehicle. However, any other vehicles that Westfield Sportscars sell, must go through the Individual Vehicle Approval (IVA) process, where each car is individually tested for conformity to the regulations. The regulations for IVA are contained within the Individual Vehicle Approval (IVA) Manual for Vehicle Category M1 (Passenger Vehicles) [77].

To understand the road requirements, an analysis of the regulations contained within the Individual Vehicle Approval (IVA) Manual for Vehicle Category M1 (Passenger Vehicles) was undertaken. Any regulations that were perceived to have the potential to affect, or be affected by, a hybrid drivetrain were identified and analysed. It was found that the regulations applicable to a hybrid electric drivetrain also relate to the braking system, and by keeping the conventional braking system, these regulations could be met. More information on the analysis of the road and motorsport regulations is shown in Submission 2 of this Engineering Doctorate [5].

5.3.1 Changes in Requirements

At the start of the Engineering Doctorate, the regulations governing club motorsport in the UK were included in the MSA ‘Blue Book’ [78]. Primarily due to events such as EV Cup, the MSA have drafted new rules regulating vehicles with alternative drivetrains [79]. Although also in draft form, these regulations are based on regulations the FIA have drafted as an aid to hybrid and electric vehicles competing in FIA sanctioned events [80]. Many of these regulations are based on the regulations contained within ISO/DIS 6469, Part 3, which defines suggested standards to protect people from electric shock, in terms of isolations and insulation of high voltage components [81].

These regulations do not impact the requirements of the system, or constrain the system to any type of hybrid electric vehicle, but provide guidelines on how acceptable levels of safety can be achieved. While these components will have an effect on the detailed design of components, to ensure they meet the safety requirements, they do not restrict the design of the drivetrain at a system level. Examples of these regulations include:

- Appropriate marking of high voltage components
- Insulation requirements for high voltage cable
- Recommended isolation values between the chassis and high voltage components
- Finger protection for connectors
- Tests to measure withstand voltages of isolation barriers
- Clearance and creepage for battery terminals from [81]
    - Clearance is defined as the shortest distance in air between two conductive parts
    - Creepage is defined as the shortest distance along the surface of a solid insulating material between two conductive parts
- Emergency Stop circuit requirements
- Safety Indicators
- Battery design requirements

5.4 Discussion

The company, motorsport and road requirements of a hybrid electric drivetrain, for installation into a Westfield Sportscars Sport Turbo racing car, have been investigated. The company requirements provided an initial direction with which to begin the project, as shown in Table 11. Analysis of the safety regulations contained with the MSA 'Blue Book' and the IVA Manual has shown that there were no specific regulations for alternative drivetrains. The only regulations that may have an effect on the design of a hybrid electric vehicle drivetrain are those relating to the vehicle braking system.

From the interview with Dr. Paul Faithfull, it was clear that it is expected that the drivetrain be developed primarily for performance and motorsport use. Improvements in fuel economy would be fine, but would probably be as a by-product of hybridisation and should not be a design target. While performance can be quantified in many ways (maximum speed, acceleration, handling, lap times), it was clear that the main aim of the project should be to reduce the 0 to 26.8ms^{-1} (0-60mph) acceleration time of the vehicle to 3 seconds. If the vehicle is capable of this, then any negative effects on handling and top speed could be accepted, assuming the pleasure gained from driving the car was not impacted.

The reason for the emphasis on 0 to 26.8ms^{-1} (0-60mph) is largely based around the requirement of publicity for the drivetrain. While acceleration is one part of vehicle performance, to increase overall performance, other aspects, such as top speed and handling are also important. However, it was felt that these aspects would be difficult to quantify and therefore difficult to generate publicity with. Therefore, the main design aim was specified by Potenza Technology to be to reduce the 0 to 26.8ms^{-1} (0-60mph) acceleration time of the vehicle, while minimising the effect on other attributes such as handing and maximum speed. If the vehicle is still 'fun' the drive, then these compromises can be justified by Potenza technology, particularly as in a race series they would be competing against like for like vehicles.

5.5 Conclusions

This requirements analysis has achieved the outcome outlined within the methodology, in that it has detailed all of the technical requirements specified by supporting company, the MSA and the VCA. The main design target identified by Potenza Technology was that the system should allow a Westfield Sportscars Sport Turbo to achieve a 0 to 26.8ms^{-1} (0-60mph) time of 3 seconds. All other technical requirements, specified by the supporting company, are detailed in Table 11. There were no additional requirements specified as a result of investigating the motorsport and road requirements.

The successful implementation of these requirements would result in a new type of drivetrain for club motorsport and an innovative product for Westfield Sportscars to sell. Although not a new concept in motorsport, hybrid electric vehicles have not been attempted in the club motorsport sector. One reason for this may be the costs involved in developing such a system. If a system could be developed so that it was not cost prohibitive, this would demonstrate innovation in this sector and could result in Westfield Sportscars leading being a technology leader in the club motorsport sector.

6 CUSTOMER SURVEY

6.1 Introduction

There are currently no hybrid electric vehicles in club motorsport. A new hybrid electric vehicle, to be considered innovative, will need to be designed to meet the unique customer requirements in the club motorsport industry. Unfortunately, there was little information, other than anecdotal evidence, on the customer requirements for such a system. It was therefore necessary to investigate what the potential customers expect from a vehicle. This was carried out through the use of a customer survey.

This investigation was carried out prior to the use of hybrid electric vehicles in professional motorsport. Therefore, there was the possibility of negative perceptions of using hybrid vehicles in motorsport due to the majority of hybrid electric vehicles being primarily designed for fuel economy gains. For this reason, to ensure no effect on the data by these perceptions, no mention of alternative drivetrains was made during data collection.

There are a number of vehicle optional extras, such as ABS and four wheel drive, that are typically not used on club motorsport cars as they are seen to add weight, cost and complexity and ultimately reduce the performance of the vehicle. However, it is possible that these optional extras could be implemented as part of a hybrid system with no reduction in vehicle performance.

The aim of this chapter is to investigate the customer requirements of a vehicle for club motorsport use by looking at typical vehicle usage, attribute importance and willingness to accept optional extras (given no reduction in performance). The scope of this chapter does not include the response of customers to hybrid electric vehicle technology in club motorsport. As there was a possibility of an initial negative response to the use of alternative drivetrains in club motorsport, this was investigated using a conjoint analysis technique, documented in chapter 7.

6.2 Methodology

The customer survey focused on general attributes of a Westfield Sportscars product. The survey was distributed through a web based interface, made available on the Westfield Sportscars internet homepage. To ensure that the correct demographic of people, current and potential customers of Westfield Sportscars and similar manufacturers, links to the survey were placed on the Westfield Owners Club internet forum as well as a general kit car forum.

To gain a better understanding of the type of participants that took part in the survey, the first question asked the participant what Westfield Sportscars product they currently own, or would be interested in owning. This was achieved by choosing the Westfield Sportscars model (SE, XTR or XI) alongside the popular engine choices for these vehicles. An 'other' option was included for each model to allow the respondent to choose a different engine. The second question asked what percentage of the time their car is (or would be) used on the track. Table 12 shows the possible answers that respondents were able to give.

Question 1 - Westfield Model	Question 2 - Road/Track Use
SE: 1.6l Ford Sigma	100% Road
SE: 2.0l Duratec	90% Road / 10% Track
SE: 2.5l Ford ST220	80% Road / 20% Track
SE: Ford Crossflow	70% Road / 30% Track
SE: Ford Zetec	60% Road / 40% Track
SE: Ford Pinto	50% Road / 50% Track
SE: Mazda MX-5	40% Road / 60% Track
SE: Vauxhall Redtop	30% Road / 70% Track
SE: Suzuki Hayabusa	20% Road / 80% Track
SE: Honda Fireblade	10% Road / 90% Track
SE: Honda Firebird	100% Track
SE: Other	
XTR: 1.8l VAG Turbo	
XTR: Hayabusa	
XTR: Other	
XI: BMC "A" Series	
XI: Other	

Table 12. Customer Survey Questions 1 and 2

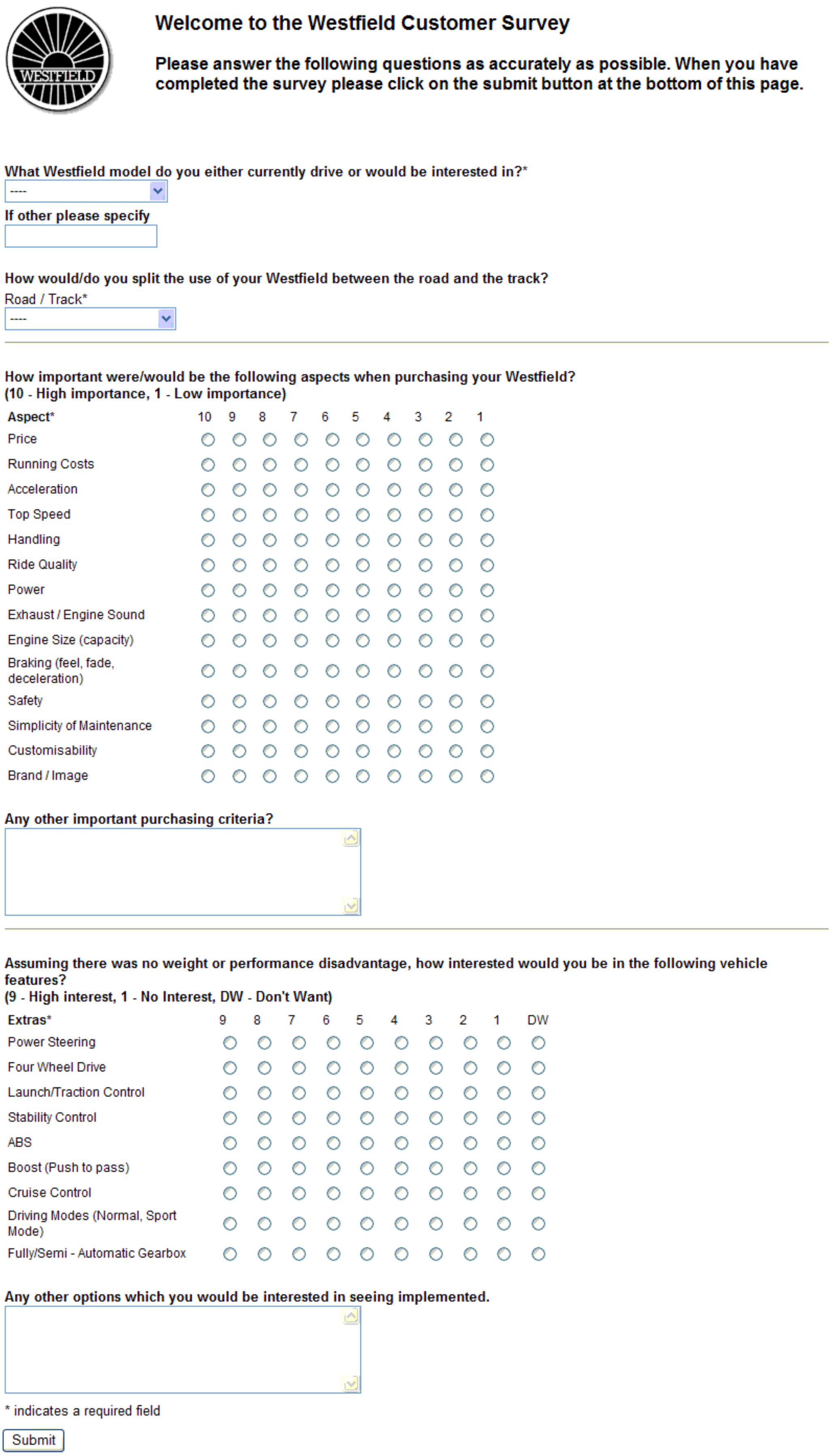
The third question gave a list of vehicle attributes that may be used to describe a Westfield Sportscars product and asked the participants to rate each attribute between 1 and 10 (10 being of highest importance). The list of attributes was compiled from hybrid electric vehicle attributes defined by the Premium Automotive Research & Development group at the University of Warwick [82, 83] and those suggested by Potenza Technology. The attributes are shown in Table 13.

The fourth question gave a list of vehicle optional extras that are not currently offered by Westfield Sportscars and asked participants to rate them between 1 and 9 (9 being of highest importance). A maximum value of 9 was used to keep the total number of radio buttons to ten, the same as question three, whilst allowing the inclusion of a DW (Don't Want) option. This allowed the participant to identify any extras that would make the product less appealing. The usual reason for this would be if it was perceived that inclusion of the optional extra hampered performance. For example, ABS (Anti-lock Braking System) has been traditionally omitted from this type of vehicle as it is believed that you can brake more effectively on the racing track if you do not have ABS.

The list of optional extras was comprised of extras that could potentially be achieved through the addition of some form of hybrid drivetrain. The optional extras are shown in Table 13. The customer survey is shown in Figure 17.

Attributes	**Optional Extras**
Price	Power Steering
Running Costs	Four Wheel Drive
Acceleration	Launch/Traction Control
Top Speed	Stability Control
Handling	ABS
Ride Quality	Boost (Push to Pass)
Power	Cruise Control
Exhaust / Engine Sound	Driving Modes (Normal, Sport Mode)
Engine Size (Capacity)	Fully/Semi Automatic Gearbox
Braking (feel, fade, deceleration)	
Safety	
Simplicity of Maintenance	
Customisability	
Brand / Image	

Table 13. Initial Survey Attributes and Optional Extras



Welcome to the Westfield Customer Survey

Please answer the following questions as accurately as possible. When you have completed the survey please click on the submit button at the bottom of this page.

What Westfield model do you either currently drive or would be interested in?*

If other please specify

How would/do you split the use of your Westfield between the road and the track?

Road / Track*

How important were/would be the following aspects when purchasing your Westfield?
(10 - High importance, 1 - Low importance)

Aspect*	10	9	8	7	6	5	4	3	2	1
Price										
Running Costs										
Acceleration										
Top Speed										
Handling										
Ride Quality										
Power										
Exhaust / Engine Sound										
Engine Size (capacity)										
Braking (feel, fade, deceleration)										
Safety										
Simplicity of Maintenance										
Customisability										
Brand / Image										

Any other important purchasing criteria?

Assuming there was no weight or performance disadvantage, how interested would you be in the following vehicle features?
(9 - High interest, 1 - No Interest, DW - Don't Want)

Extras*	9	8	7	6	5	4	3	2	1	DW
Power Steering										
Four Wheel Drive										
Launch/Traction Control										
Stability Control										
ABS										
Boost (Push to pass)										
Cruise Control										
Driving Modes (Normal, Sport Mode)										
Fully/Semi - Automatic Gearbox										

Any other options which you would be interested in seeing implemented.

* indicates a required field

Submit

Figure 17. Customer Survey

To determine the margin of error for a given survey, the equation shown in Equation 3 can be used where c is the margin of error (confidence interval), z is the multiplier used to calculate to a given confidence level (z = 1.96 for a 95% confidence level), N is the population size, n is the sample size and p is the variability in the data (a value of 0.5 was used for p as it represents the worst case scenario).

$$c = \mathrm{z} \times \sqrt{\frac{p(1-p)}{n} \times \frac{N-n}{\mathrm{N}-1}}$$

Equation 3

6.3 Results

The survey was posted on the Westfield Sportscars website for a period of two weeks in June 2007. To encourage people to take part in the survey, posts pointing the survey were placed on Westfield Sportscars Owners Club forum and on a general kit/racing car forum. The survey received 248 responses.

Using data from the Society of Motor Manufacturers and Traders (SMMT), it can be seen that there were 65,731 ‘Specialist Sports’ cars sold in the UK during 2007 [84]. Using this as a populations size (N) and the 248 respondents as the sample size (n), a variability of 0.5 (p) and 95% confidence interval (z = 1.96) the level of precision can be seen to be 0.062. Therefore, the results of the survey can be seen to have a 95% confidence level with ±6.2% level of precision (i.e. it can be inferred, with 95% surety, that the survey represents the population with the results having an accuracy of ±6.2%).

The full results to questions 1 and 2 are shown in Submission 2 of this Engineering Doctorate [5]. The results show that the majority of customers own (or would consider owning) a Westfield Sportscars SE of some type. It also showed that the majority of customers, 78%, used their cars on the track to some degree (10% of the time or greater).

The average scores and standard deviations of the vehicle attributes are shown in Table 14. Figure 18 shows the averages of the vehicle attributes, ordered by highest average customer rating. It can be seen that the performance attributes, such as ‘Handling’, ‘Braking’, ‘Acceleration’ and ‘Power’ score the highest with Westfield Sportscars’ customers (between 9.42 and 8.12). These attributes also have the lowest standard deviations (between 0.97 and 1.65).

Attribute	Average Score	Standard Deviation
Price	7.80	2.07
Running Costs	5.07	2.63
Acceleration	8.74	1.54
Top Speed	6.54	1.84
Handling	9.42	0.97
Ride Quality	7.15	2.03
Power	8.12	1.65
Exhaust / Engine Sound	7.29	2.07
Engine Size (Capacity)	6.01	2.09
Braking (feel, fade, deceleration)	8.75	1.39
Safety	7.39	2.19
Simplicity of Maintenance	7.12	2.24
Customisability	7.32	2.37
Brand / Image	6.94	2.26

Table 14. Vehicle Attribute Averages and Standard Deviations

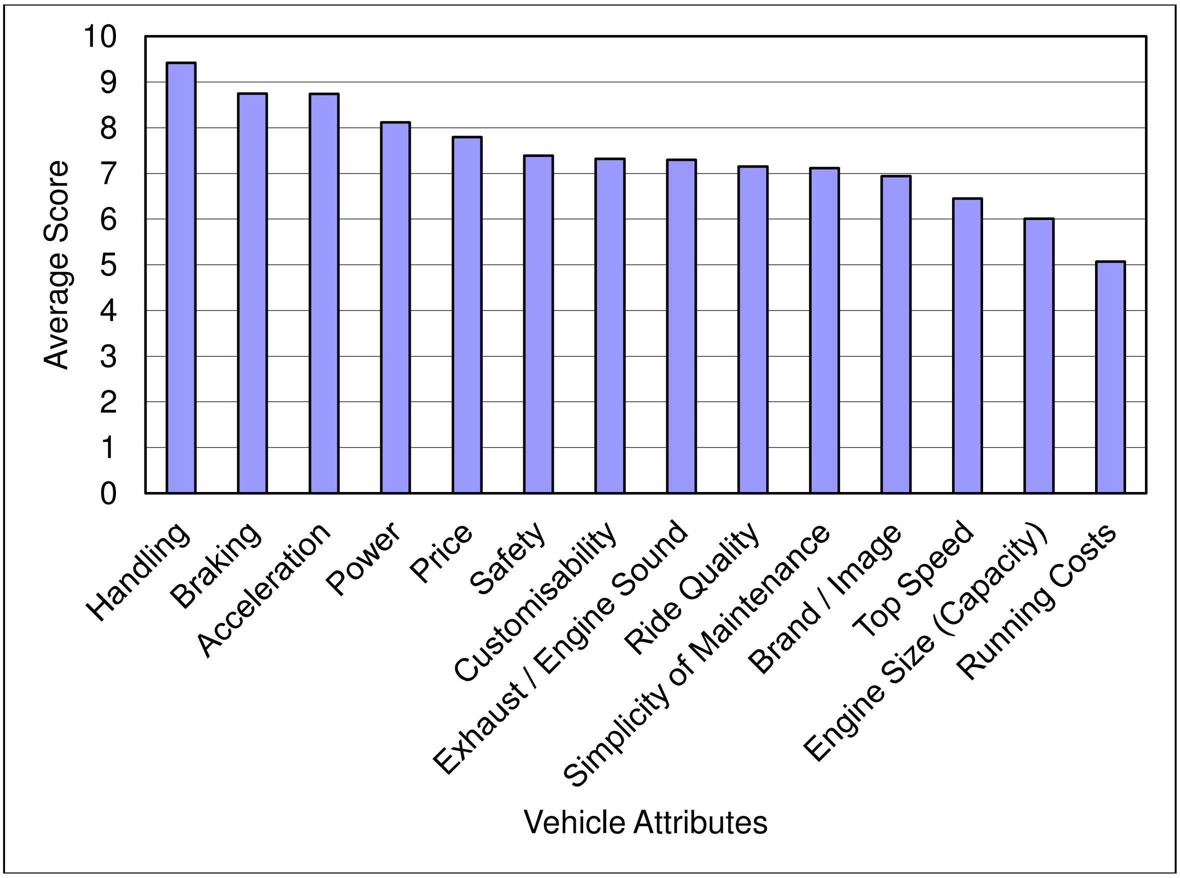


Figure 18. Vehicle Attributes Averages

Other attributes that could be seen to be related to vehicle performance, such as ‘Top Speed’ and ‘Engine Size’ scored poorly in comparison. ‘Running Costs’ was the attribute that received the lowest rating; it also had the highest standard deviation. This suggests that people’s attitude to ‘Running Costs’ has a higher variation than other attributes. The distribution of scores of the ‘Running Costs’ attribute is shown in Figure 19 where it can be seen that the scores are mainly distributed between one and eight, with no single score appearing to be significantly more popular than the others. This suggests that there is a more complex importance associated to this attribute and further investigation may be required to understand this.

Figure 19. Running Costs Scores

The average scores and standard deviations for the optional extras are shown in Table 15 and Figure 20. A value of zero was used for scores of ‘Don’t Want’. It can be seen that the average scores of the optional extras are low (the highest being 4.48), suggesting that in general the participants did not want to see any of these optional extras on a Westfield Sportscars product. The standard deviations were high compared to the standard deviations related to the vehicle attributes, suggesting that there was more variance in the scores received. The average standard deviation for the optional extras was 2.91. The average standard deviation for the vehicle attributes was 1.95.

Optional Extra	Average Score	Standard Deviation
Power Steering	1.94	2.61
Four Wheel Drive	2.89	3.13
Launch/Traction Control	4.48	3.20
Stability Control	3.09	3.02
ABS	3.99	3.26
Boost (Push to Pass)	3.58	3.17
Cruise Control	1.21	2.05
Driving Modes (Normal, Sport Mode)	2.20	2.70
Fully/Semi Automatic Gearbox	2.63	3.07

Table 15. Optional Extras Average Scores and Standard Deviations

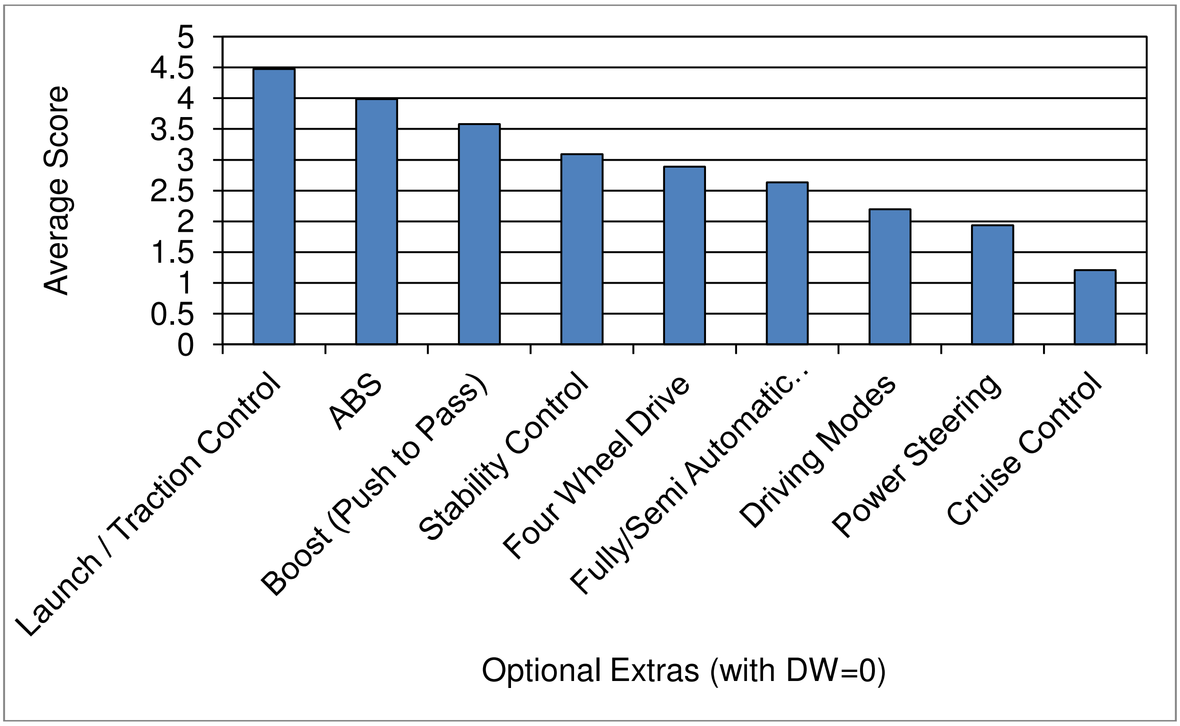


Figure 20. Optional Extras Average Scores

6.3.1 Track vs. Road

Figure 21and Figure 22 show the average scores for the attributes and optional extras against the average scores for track drivers and road drivers. A road driver was described as one who declared their car was used on the road for 50% of the time or more and a track driver was calculated as one who declared their car was used on the track for 50% of the time or more. Where the respondent answered “50% Road / 50% Track”, the scores were halved between the two groups.

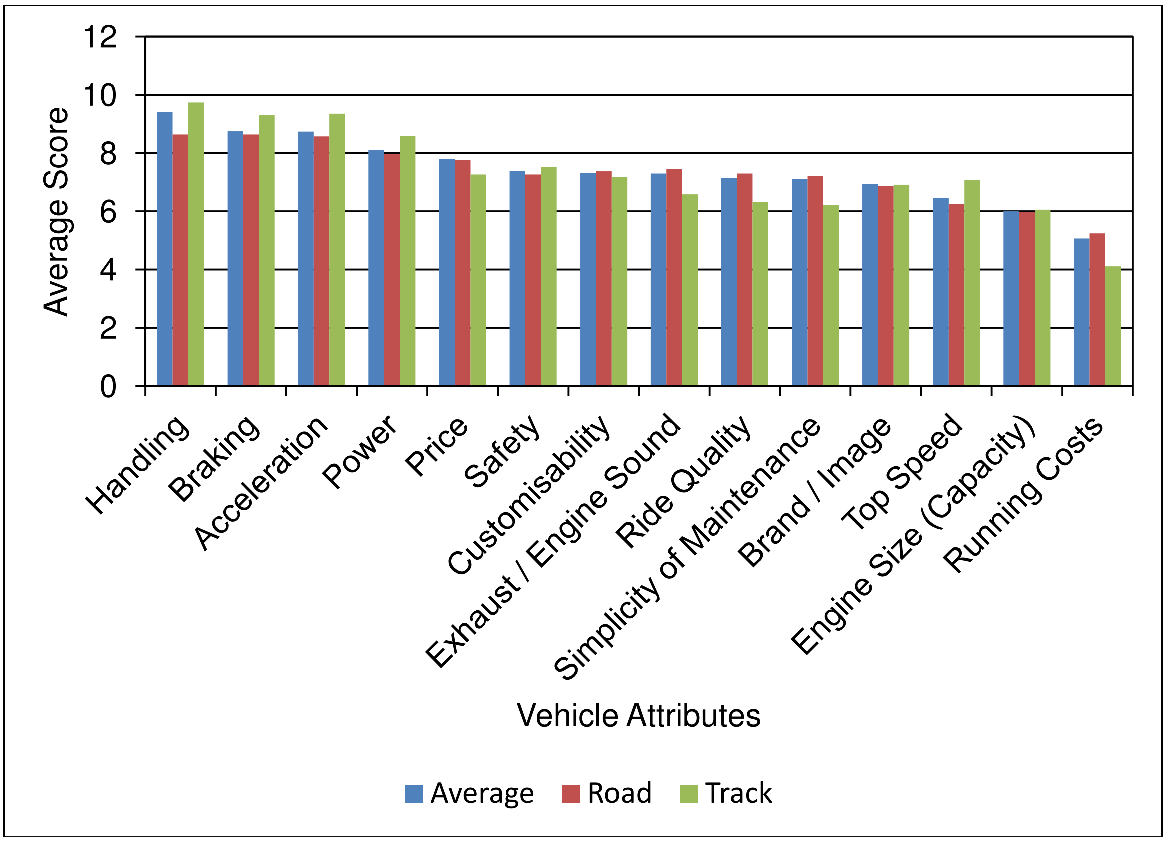


Figure 21. Track vs. Road Attributes

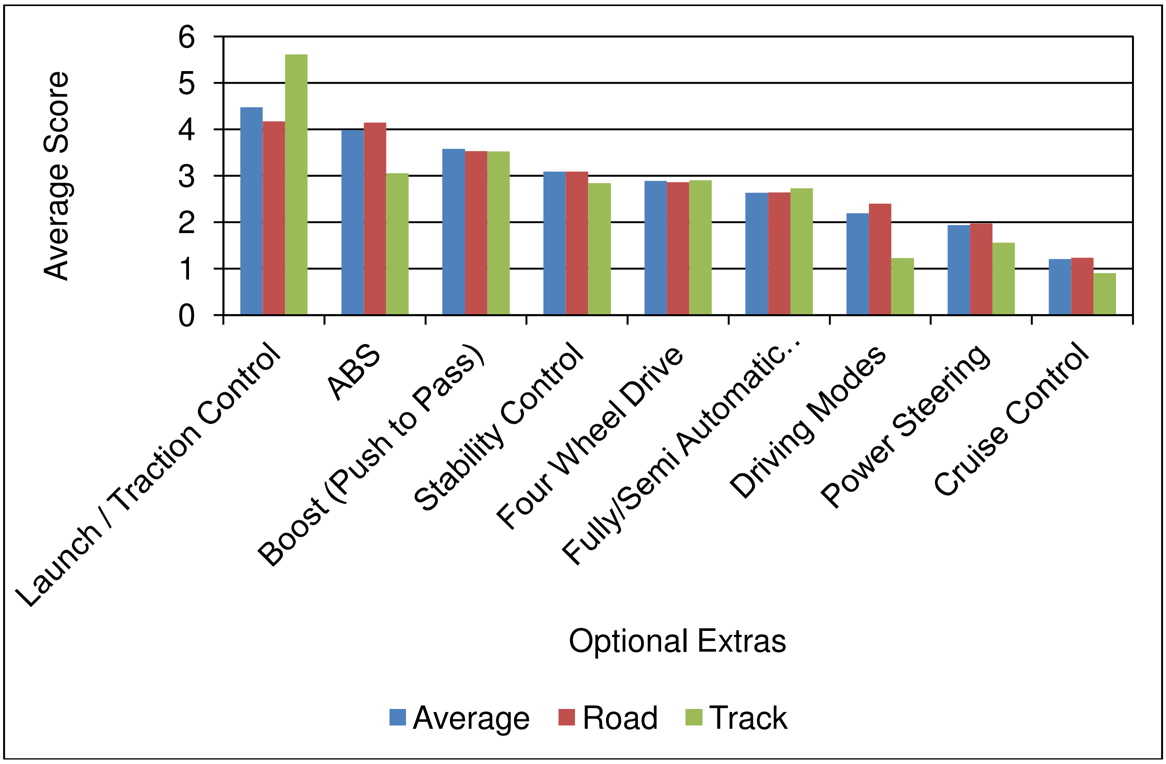


Figure 22. Track vs. Road Optional Extras

It can be seen that generally the relative importance of each attributes between the road and track users is similar. However, there are differences in the magnitude of the importance of each attribute. For example, the scores received for handling, braking and acceleration are higher for the track users than the road users. This is because these attributes will have more significance in a race situation.

In addition, top speed has a higher average rating by the track users than the road users, but this higher rating would only make it the 8^{th} most important attribute for track users and is therefore not significant. Running costs have been rated as much lower than the average or road user scores and this could be reason why there appeared to be no single running costs score more popular than the others. Figure 23 shows how the scores for running costs were split between the road and track users. It can be seen that the scores provided by the road users for running costs average to 5.24 and appear to cluster around this point. However the scores provided by the track users shows no obvious trend.

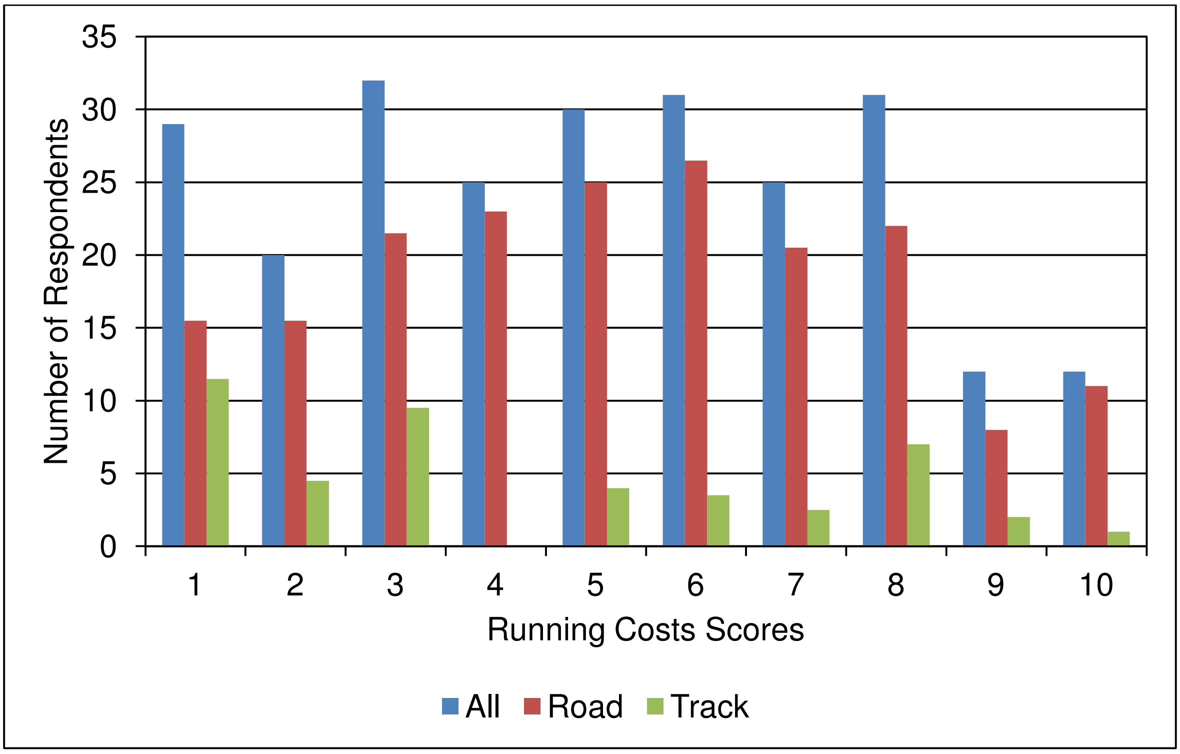


Figure 23. Track vs. Road Running Costs Scores

For the optional extras, the relative importance of the optional extras is similar between the road and track users, with two obvious exceptions, launch/traction control and ABS. The track users rated launch/traction control much higher than the road users. This is because launch/traction control will have a large impact on racing performance. The track users also down rated the importance of ABS. This is because ABS is seen as a safety device for use on the road, but can negatively impact performance on a race track [4]. The result of this is also that boost (push to pass) becomes the second most important optional extra for the track users.

6.4 Discussion

A survey approach has been used to look at the customer requirements of a vehicle in club motorsport. While the aim of the project is to develop a hybrid electric vehicle solution for motorsport, the survey purposefully did not mention hybrid electric vehicle technology and therefore can be seen to be representative of the customer requirements of any vehicle sold into this market.

The results showed that customers, rate aspects such as handling, braking, acceleration and power highly. This is most likely to be due to the fact that these factors directly influence performance and therefore the enjoyment that a driver has from the vehicle, which is important within the club motorsport industry. Had 'Driving Enjoyment' been included as a rateable attribute it would have been interesting to see how it scored. However, as it is a subjective attribute, and is possibly made up of a combination of other attributes, it may not have provided much further insight.

The price of the vehicle was the fifth highest rated vehicle attribute, suggesting that there may be scope to increase the price of the vehicle as long as the other performance related attributes are also improved. This would suggest that, to develop an innovative hybrid electric drivetrain for a Westfield Sportscars platform, any additional price increase would need to be justified through appropriate performance increases. Further work is therefore required to understand the effect of performance increases on the vehicle price customers would be willing to pay.

While given a poor average score, running costs received the largest variability in scores. It was shown that, while on average people do not rate it highly, there were some respondents who scored it higher than other attributes. The running costs attribute was included to represent items such as servicing costs, tyre costs and fuel economy. This may explain why a large variation in scores was seen and it is possible that the results are bimodal in nature as well as different types of user (track and road) giving the attribute very different scores. While fuel economy gains are not the aim of this work, if this technology does transfer to the road, fuel economy gains may be expected of an innovative hybrid electric drivetrain for club motorsport. Therefore, given the varied nature of the responses to the running costs attribute and the potential future implications of fuel economy of the popularity of the system, the effect of fuel economy is worthy of further investigation.

Investigations into the difference between road and track users has shown that whilst there are some differences in the magnitude of scores, the ranking of the attributes and the optional extras are similar. An explanation for this may be that the motivations for purchasing a Westfield are similar for both road and track drivers due to the aspitrational association of the brand to motorsport. Therefore, the use of the average scores from all of the participants provides an accurate picture of attribute importance and the market for the optional extras.

6.5 Conclusions

It has been shown that the most important attributes for the customer are handling, braking, acceleration, power and price. The supporting company, Potenza Technology, have stated that the aim of the project, for mainly publicity reasons, is to reduce the acceleration time of the vehicle and some impact on aspects, such as handling and braking would be tolerated. Therefore, in line with the objective outlined in the methodology for this chapter, the attributes which will be investigated in the following conjoint analysis survey will be acceleration, handling power and price.

It has also been identified that fuel economy is worthy of further identification, due to the bimodal nature of the results of the survey, and this will also be investigated in the conjoint analysis. The type of drivetrain was not investigated in this survey in an attempt to stop pre-conceptions of hybrid powertrains having an impact on the results. This will also be investigated in the conjoint analysis.

It was expected by Potenza Technology that optional extras that could be realised through the integration of a hybrid drivetrain would increase the appeal of a hybrid drivetrain. The low scores that the optional extras receive indicate that the demand for these optional extras is low and that, for a system to be successful and demonstrating innovation, it should be primarily designed for performance benefits and not optional extras. Therefore, optional extras will not be investigated any further.

7 CONJOINT ANALYSIS

7.1 Introduction

A customer survey has been carried out that has looked at the customer requirements for a vehicle in the club motorsport market. It was shown that performance aspects, such as handling and acceleration, were rated higher than price. It was also found that the effect of running costs, such as fuel economy may be suitable for further investigation. This investigation did not look at the effect of alternative drivetrains on consumer preference.

Therefore, to understand the relationship between performance, price, drivetrain and fuel economy, further investigation is required. One method of doing this is through a conjoint analysis survey. The results of which can then be used to build a market simulation tool that can predict the preference share of a given drivetrain.

Conjoint analysis has been used for many years to investigate consumer preference towards existing product attributes. This information can then be used to predict consumer preference to new product attributes. This will typically be carried out by creating a simulation tool to compare existing products against a new product profile, assuming the new product data lies within the gathered data [85-87].

Conjoint analysis has been used successfully in the past to both determine the pricing and assist in new product development for vehicles with alternative drivetrains. Dagsvik et al. performed a conjoint analysis to analyse the potential demand for alternative fuel vehicles, in particular liquid propane gas, electric and dual-fuel vehicles in Norway [88]. The attributes investigated were purchase price, driving range, top speed and fuel consumption. These attributes were chosen based on a pre-survey and focus groups. It was concluded that alternative fuel vehicles appear fully competitive against conventional gasoline vehicles. They found that purchase price and driving range were the most important attributes.

A similar survey was undertaken by Ahn et al. looking at the effect of introducing alternatively fuelled passenger cars in South Korea [89]. The attributes used to carry out the conjoint analysis were fuel type, body type, maintenance cost, engine displacement, fuel efficiency and fuel price. It was concluded that if the purchase price of alternatively fuelled vehicles was similar to that of conventional passenger cars, then they will occupy a significant portion of the market.

A large conjoint analysis survey was carried out by Brownstone et al. on vehicle demand in California with 4747 households taking part [90]. The model found that vehicle range was of high importance, with acceleration time being more important for households with high income. The paper concludes that conjoint analysis provides a realistic approach to gauge the future demand for alternative fuelled vehicles.

Eggers and Eggers carried out a conjoint analysis comparing hybrid and electric vehicles to conventionally fuelled vehicles [91]. The attributes investigated were drivetrain type, range and price compared to conventionally fuelled vehicles. The study showed a general acceptance of alternatively fuelled vehicles, in particular parallel hybrids, with the major determining factors being the range and price of the vehicle. The estimated adoption of series hybrid and electric vehicles (6.3% and 2.3% respectively) was found to be significantly lower than parallel hybrids (57.9%)

While all these conjoint analysis surveys have shown the vehicles with alternative drivetrains (including hybrid electric vehicles) can compete with conventionally fuelled vehicles, the surveys concentrate on passenger vehicles and not specialist vehicles (such as club motorsport). There is no published literature that has shown a conjoint analysis approach being used in the motorsport industry to gain a deeper understanding of customer requirements. Therefore, the aim of this chapter is to investigate the relationship between vehicle performance, price, drivetrain type and fuel economy in club motorsport vehicles using a conjoint analysis approach.

7.2 Alternative Approaches

While conjoint analysis was chosen, there are a number of alternative approaches to understanding consumer preference that could have been used [92]. These are:

- The Kano model
- The product value matrix
- The lead user model

- Quality function deployment, house of quality.

The Kano model is a method of prioritising product attributes based on characterising the attributes into four groups [92]. While the Kano model provides a good tool for characterising attributes, it does not allow for the more complex predictive analysis that can be obtained with a conjoint analysis. However, it has been suggested that the Kano model can be used to help choose product attributes for use in a conjoint analysis [93].

The product value matrix is a tool for ensuring that new product development plans address the needs and requirements of all stakeholders in the value chain [92]. It is not designed to compare the importance of attributes and is therefore not relevant to the initial concept design of a hybrid drivetrain for motorsport. The lead user method involves identifying a products lead users and using them to assist in development of a new product [92]. However, in the club motorsport market, there was very little understanding of hybrid electric vehicles and the benefits that can be realised by them, making the lead user method not suitable.

Quality function deployment, house of quality is a method of building quality into the product design from the outset by linking quality expectations to technical requirements [92]. Part of this process involves weighting customer requirements against the technical requirements to ensure that the most important requirements are met. However, to do this, an understanding of the attribute importance is required. Because the weightings customer requirements for a hybrid drivetrain for motorsport are unknown this method could not be used. However, it is possible to use conjoint analysis to determine attribute importance weightings as part of a house of quality approach to product design [93].

7.3 Methodology

7.3.1 Conjoint Analysis

A full profile choice based conjoint analysis approach was used to develop the conjoint analysis. A full profile choice based conjoint analysis requires that two product profiles are generated, based on a number of attributes, with discrete levels randomly assigned to each attribute. The participants were asked to rate which of the two product profiles they prefer. In total the participants were asked to rate twenty pairs of randomly generated product profiles. The attributes used in the conjoint analysis survey were:

- Engine Power
- 0 to 26.8ms^{-1} (0-60mph) Acceleration
- Fuel Economy
- Price
- Drivetrain type

A screen shot of the conjoint analysis and the product profiles is shown in Figure 24. The levels for each attribute are shown in Table 16. Imperial units were used to describe the levels (bhp, mph, mpg) as these numbers are used in common language and the participants were more likely to understand these units. In the same way as the customer survey, the conjoint analysis was distributed through a web based interface, made available on the Westfield Sportscars internet homepage. Links to the survey were placed on the Westfield Owners Club internet forum as well as a general kit car forum to ensure that the correct demographic of people saw and took part in the survey.

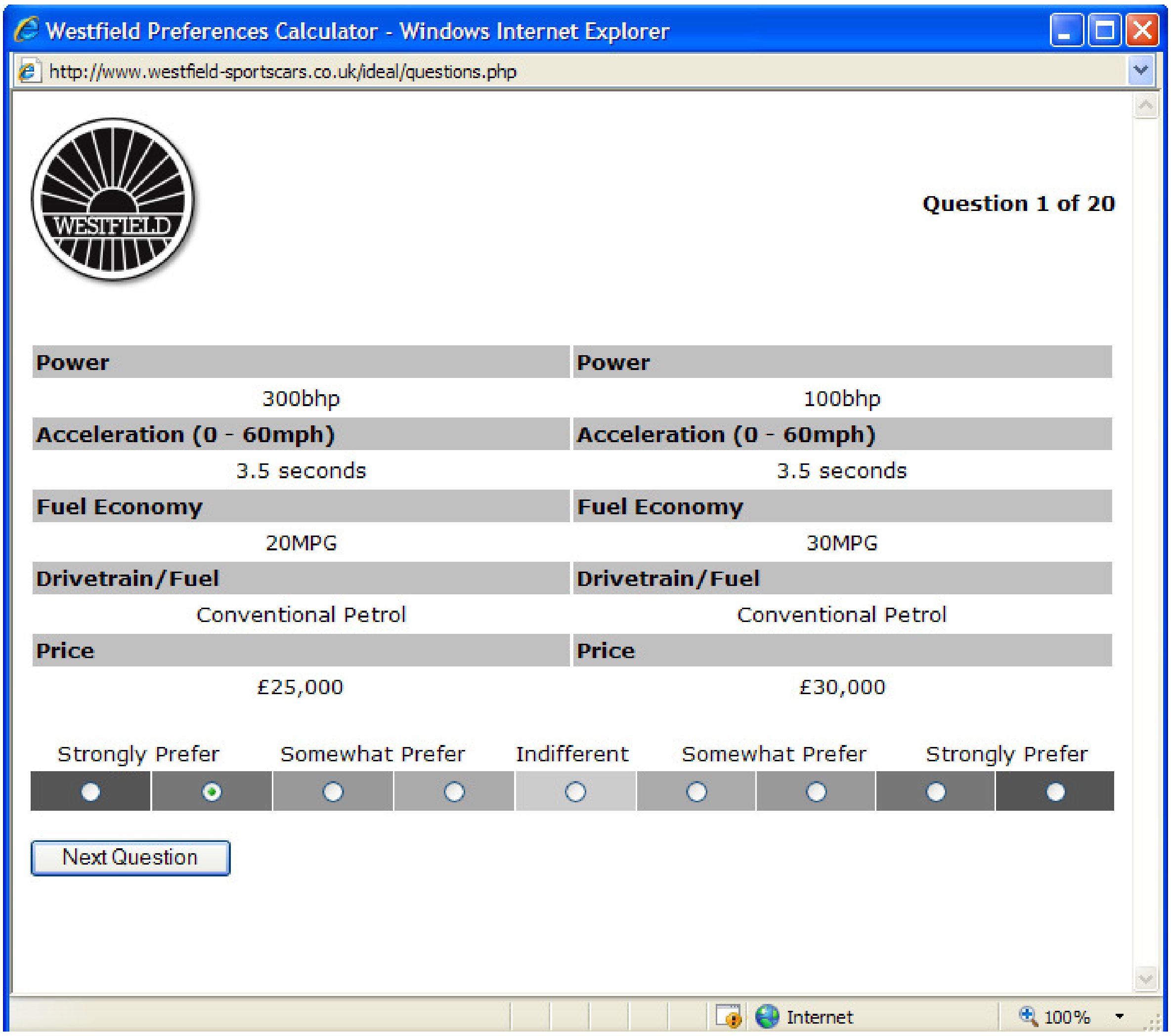


Figure 24. Conjoint Analysis Screen Shot

Attributes	**Levels**
Engine Power (BHP)	100, 150, 200, 300, 350
0 to 26.8ms^{-1} (0-60mph) Acceleration Time	2.5, 3, 3.5, 4, 4.5, 5, 6
Fuel Economy (MPG)	15, 20, 25, 30, 50, 100
Price (thousand GBP)	15, 20, 25, 30, 35, 40
Drivetrain Type	Conventional Petrol Conventional Diesel Conventional Bio-Fuel Hybrid Petrol Hybrid Diesel Hybrid Bio-Fuel

Table 16. Conjoint Analysis Attributes and Levels

Acceleration, engine power and price were chosen because they were found to be important in the initial survey. Although handling and braking were also identified as important, it is not possible to quantify these attributes into a value for comparison purposes in a conjoint analysis. Whilst, in the initial survey, running costs were found on average to be the least important attribute, it was found that there was a large variance in the scores it received and therefore appropriate for further investigation. For this reason fuel economy was included in the conjoint analysis as it is a significant aspect of a vehicle's running costs and is relevant to hybrid and electric vehicles. Drivetrain type was included to investigate the effect on customer preference of having the choice of a hybrid drivetrain as well as conventional drivetrains (bio-fuel and diesel drivetrains were also included). A product profile comprised of a randomly generated level for each of these attributes, with the respondent asked to compare 20 pairs of randomly generated product profiles.

During the survey, when a respondent indicated that they preferred one product profile over another, a database was updated giving the levels on the product profile that was preferred a positive value and the levels on a product profile that was not preferred a negative value. The level of preference that could be chosen through the radio buttons, shown in Figure 24, updated the levels by either 0 (for indifferent), 0.25, 0.5, 0.75 and 1. Each participant had its own database entry.

In the example shown in Figure 24, the database entry for the participant would be updated with +0.75 added onto the score of each of the levels shown on the left. Each of the levels shown on the right would be updated with -0.75. In this example, the scores for 3.5 seconds and conventional petrol would not be updated as they would cancel each other out as they appear in both product profiles. This was repeated twenty times for each participant, with randomly generated product profiles.

For a conjoint analysis to be considered representative of the target demographic, Johnson and Orme, suggest that, for a full profile choice based conjoint analysis, Equation 4 should be satisfied [94], where *n* is the number of respondents, *t* is the number of tasks, *a* is the number of alternatives per task and *c* is equal to the largest number of levels of any one attribute.

$$\frac{nta}{c} \geq 500$$

Equation 4

Equation 3, used to determine the level of precision of the results in the customer survey, was also applied to the conjoint analysis. Further information on conjoint analysis, and how it can be used, can be found in the literature [87].

7.3.2 Market Simulation Tool

From the results of the conjoint analysis, a market simulation tool was devised. The market simulation tool assumed a first choice model to consumer preference. A first choice model assumes the respondents choose a product, from the product set available, based on the sum of utilities of the levels of attribute corresponding to each product.

This approach is sometimes known as a logit model. Alternative approaches are examined by Brownstone and Train [95], who suggest that the logit model is not robust enough to take into account options other than used in the market simulation tool. However, as the conjoint analysis focuses on a specialist market place, it was considered an appropriate tool to use.

Therefore a market simulation tool was developed that allowed the user to select two example vehicles (based on the attributes and levels of the conjoint analysis). The market simulation tool then determined, out of the individual respondent results of the conjoint analysis, what proportion of the respondents would choose option one over option two. This is shown in Equation 5 and Equation 6 where n_x is the number of respondents that would choose option x, n_{total} is the total number of respondents, i is the individual respondent number, ep_i^x is the utility value for engine power selected for option x and respondent i, t_i^x is the utility value for acceleration time selected for option x and respondent i, fe_i^x is the utility value for fuel economy selected for option x and respondent i, p_i^x is the utility value for price selected for option x and respondent i, d_i^x is the utility value for drivetrain type selected for option x and respondent i.

$$n_x = \sum_{i=1}^{n_{\text{total}}} f(i)$$

Equation 5

$$f(i) = \begin{cases} 0, & (ep_i^1 + t_i^1 + fe_i^1 + p_i^1 + d_i^1) < (ep_i^2 + t_i^2 + fe_i^2 + p_i^2 + d_i^2) \\ 0.5, & (ep_i^1 + t_i^1 + fe_i^1 + p_i^1 + d_i^1) = (ep_i^2 + t_i^2 + fe_i^2 + p_i^2 + d_i^2) \\ 1, & (ep_i^1 + t_i^1 + fe_i^1 + p_i^1 + d_i^1) > (ep_i^2 + t_i^2 + fe_i^2 + p_i^2 + d_i^2) \end{cases}$$

Equation 6

Equation 5 and Equation 6 can therefore be used to determine the proportion of respondents that would choose option 1 over option 2 in the two option market simulation tool.

7.4 Results

7.4.1 Conjoint Analysis

The conjoint analysis was posted on the Westfield Sportscars website for a period of two weeks in November 2007. To encourage people to take part in the survey, posts pointing the survey were placed on Westfield Sportscars Owners Club forum and on a general kit/racing car forum. The survey received 303 responses.

Using the method described by Johnson and Orme, Equation 4 was used to determine if the conjoint analysis could be considered representative of the target demographic. For this conjoint analysis; n=303, t= 20, a= 2 and c=7.

$$\frac{303 \times 20 \times 2}{7} = 1731$$

Equation 7

It can be seen from Equation 7 that the result of the equation is greater than 500; therefore it can be assumed that the conjoint analysis is representative of the target demographic.

Using the same population size as for the customer survey and Equation 3, it can be determined that the results of the survey can be seen to have a 95% confidence level with a 5.6% margin of error (i.e. it can be inferred, with 95% surety, that the survey represents the population with the results having an accuracy of ±5.6%).

The conjoint analysis resulted in a utility value being produced for each level of each attribute and for each respondent. The utility value denotes, in the context of conjoint analysis, the customer's liking for a product alternative. A high utility would indicate that the customer has a higher preference for that attribute level over an attribute level with a lower utility score.

The average utility values of the drivetrain types are shown in Figure 25. It can be seen that conventional petrol and hybrid petrol received the highest utility values, suggesting that there would be a market for a hybrid petrol Westfield Sportscars model. The drivetrain with the lowest utility value was received by the conventional diesel, with hybrid diesel also receiving a low utility value.

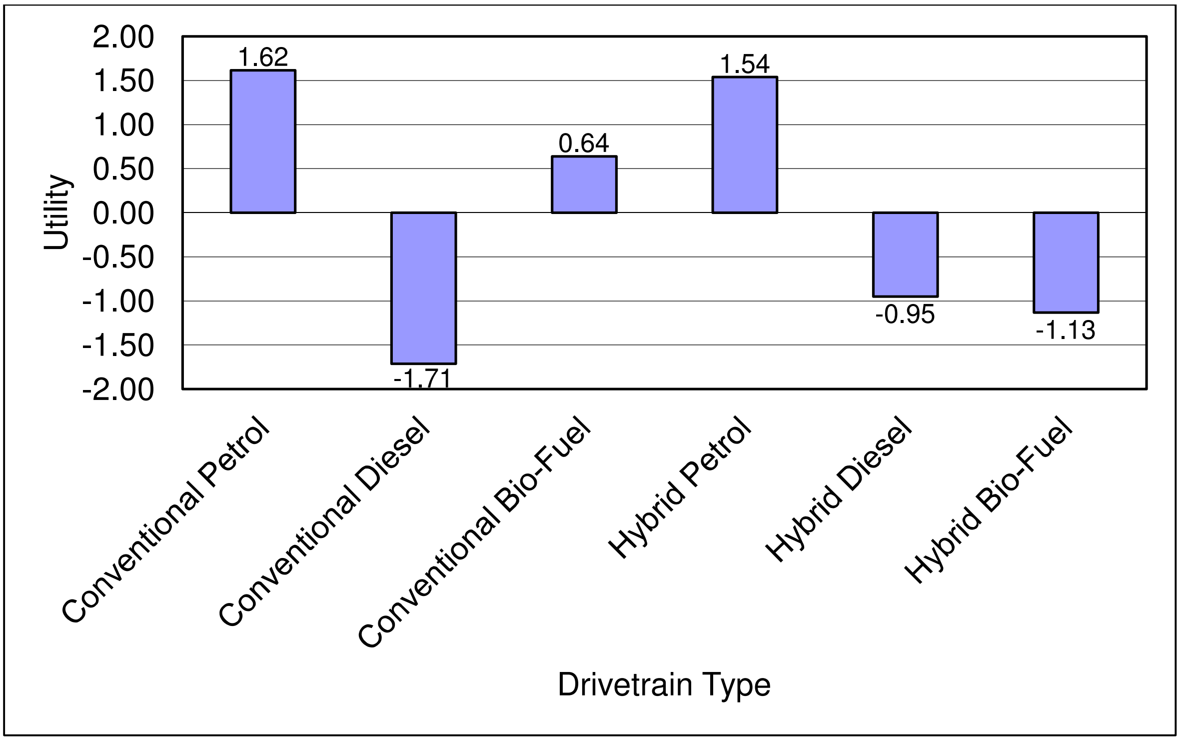


Figure 25. Drivetrain Utility Values

While this suggests that there is little demand for a diesel drivetrain, it is important to note that a low utility score does not necessarily mean that there would not be a business case in developing a diesel drivetrain (or indeed a conventional or hybrid bio-fuel drivetrain). Further work would be required to understand the likely costs of developing these systems, their likely performance and the potential market size for these systems (using the market simulation tool).

The average utility scores all of the attributes and level is shown in Table 17.

Attribute	Level	Average Utility Value
Engine Power	100 BHP	-1.47
	150 BHP	-0.76
	200 BHP	0.03
	300 BHP	0.45
	350 BHP	1.74
0 to $26.8ms^{-1}$ (0-60mph) Acceleration Time	2.5 seconds	6.07
	3 seconds	4.46
	3.5 seconds	2.36
	4 seconds	0.26
	4.5 seconds	-1.59
	5 seconds	-4.59
	6 seconds	-6.96
Fuel Economy	15 MPG	-3.71
	20 MPG	-1.68
	25 MPG	-0.90
	30 MPG	-0.08
	50 MPG	2.32
	100 MPG	4.04
Price	£15,000	6.22
	£20,000	2.96
	£25,000	1.93
	£30,000	-1.76
	£35,000	-3.06
	£40,000	-6.30
Drivetrain Type	Conventional Petrol	1.62
	Conventional Diesel	-1.71
	Conventional Bio-Fuel	0.64
	Hybrid Petrol	1.54
	Hybrid Diesel	-0.95
	Hybrid Bio-Fuel	-1.13

Table 17. Conjoint Analysis Average Utility Values

From the results of the Table 17, it can be seen that there were strong trends in the majority of attributes:

- Participants preferred engines with high power over those with low power
- Participants preferred low 0 to $26.8ms^{-1}$ (0-60mph) acceleration times over higher times
- Participants preferred higher fuel economy over low fuel economy
- Participants preferred low prices over high prices

Given what is known already about the club motorsport market, these trends are not surprising. However what is not yet known is the importance of one attribute over another, how this compares with the results obtained in the customer survey, and this will affect the design of an innovative hybrid electric drivetrain for club motorsport.

Using the utility data from the conjoint analysis, it is possible to compare the attribute importance from the initial survey with that found in the conjoint survey. Attribute importance is calculated as shown in Equation 8, where I_x is the individual attribute importance of attribute x, u_{xmax} and u_{xmin} are the maximum and minimum utilities for attribute x and y is the total number of attributes.

$$I_x = \frac{(u_{xmax} - u_{xmin})}{\sum_{k=1}^{k=y}(u_{xmax} - u_{xmin})}$$

Equation 8

Figure 26 shows the attribute importance of engine power, acceleration time, fuel economy (running costs), price and drivetrain from both surveys. There is no importance of drivetrain type from the initial survey as these data were not collected.

It can be seen from Figure 26 that the attribute importance of the acceleration time, price and fuel economy found in the conjoint analysis, closely matches the attribute importance calculated from the initial survey. The drivetrain attribute has a low attribute importance from the conjoint analysis, suggesting that it was not considered important by the respondents. The attribute importance of engine power does not correlate between the two surveys, with the results of the initial survey placing a larger importance on engine power than that seen in the conjoint analysis.

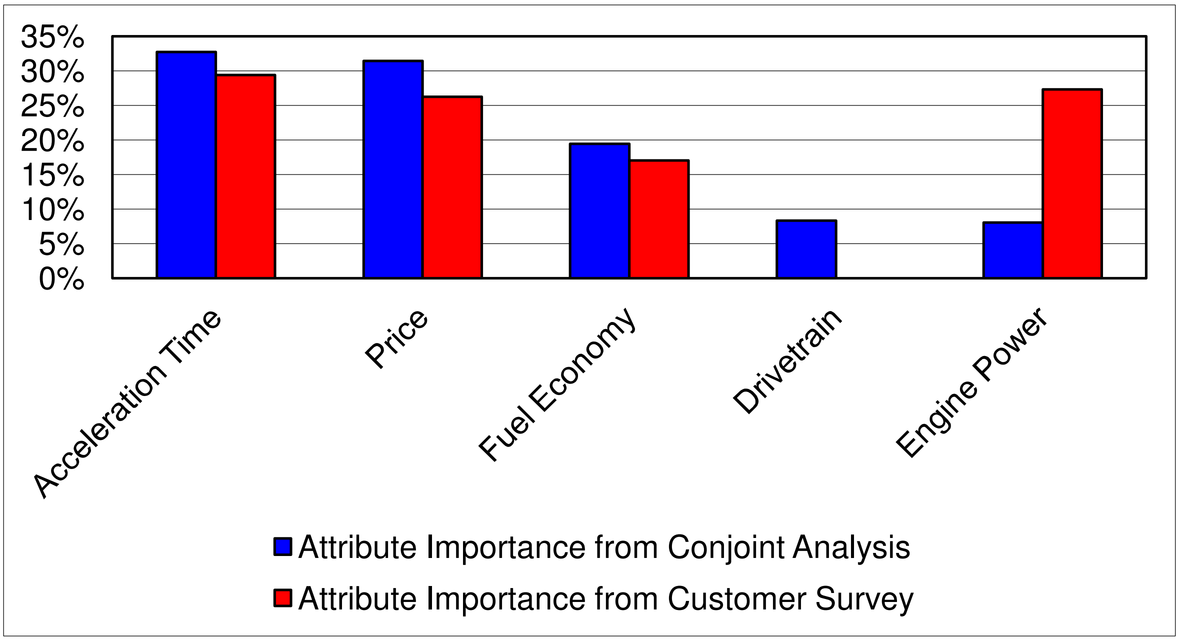


Figure 26. Attribute Importance

These results suggest that engine power, although initially identified as an important attribute, is not important to customers when comparing one vehicle to another. It is more important that the vehicle be able to accelerate than have a high engine power. This is important for vehicles with hybrid and electric drivetrains as the power characteristics of electric motors are different to that of conventionally fuelled vehicles.

The results also suggest that drivetrain type is not important, as long as the vehicle accelerates and has an attractive price. Although running costs were identified as having a low importance in the initial survey, the importance as shown in the conjoint analysis was higher. This may be due to people having the choice of a drivetrain a higher or lower fuel economy than previously expected or available and therefore attributing more importance to fuel economy.

7.4.2 Market Simulation Tool

To further investigate the importance of price on the purchasing decision, a market simulator was developed that uses the results of the conjoint analysis to estimate the preference of one vehicle product profile over another. The profiles of the vehicles used are shown in Table 18. A Westfield Sport Turbo was used as the base model, and an example hybrid drivetrain was used to understand the effect of price on preference share. The results are shown in Figure 27.

Attribute	Westfield Sport Turbo	Westfield Hybrid
Engine Power	200 BHP	300 BHP
Acceleration Time	4.5 s	3.5 s
Fuel Economy	25 MPG	30 MPG
Drivetrain Type	Conventional Petrol	Hybrid Petrol
Price	£25,000	Varied

Table 18. Simulated Vehicle Profiles

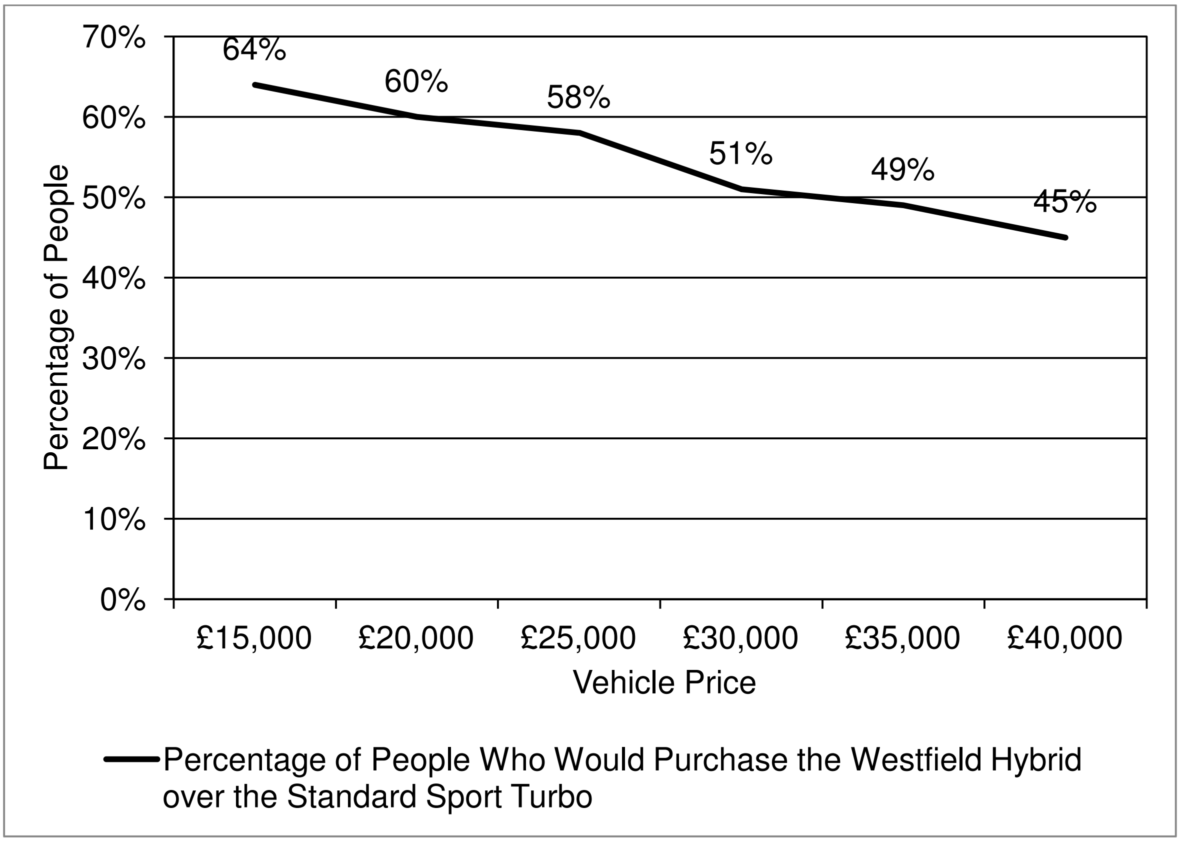


Figure 27. Westfield Hybrid Share of Preference

It can be seen that as the price of the hybrid Westfield Sportscars vehicle increases, the share of preference falls from 64% to 45%. This means that at a cost of £40,000 (an extra cost of £15,000 over base model price) 45% of people would choose the hybrid vehicle over the conventional vehicle. Combining this with the level of confidence calculations for the conjoint analysis, this indicates that if a drivetrain was developed that was similar to the simulated hybrid electric vehicle; Westfield Sportscars would be 95% sure that 45% of people, ±5.7%, would choose the hybrid vehicle over the Sport Turbo model.

7.5 Discussion

The results of the conjoint analysis have confirmed many of the assumptions that were made based on the results of the customer survey. These are that acceleration time is more important than price, which is more important than fuel economy (running costs in the customer survey). However the conjoint analysis showed that engine power was the least important attribute of the five, in contrast with it being ranked higher than price in the customer survey.

A likely reason for this is that, in the initial survey, people were asked how important they thought engine power was. Taken as an attribute in isolation, engine power may have been used to make an assumption of the vehicle's performance. Once the engine power was shown in relation to the vehicle's acceleration time, the link between engine power and performance was no longer required and the importance of engine power reduced accordingly.

This is significant for the development of a hybrid electric vehicle as, while electric motors have often preferable torque characteristics to internal combustion engines, their peak power figures are often lower than that of a comparable internal combustion engine and this may deter people from buying a hybrid electric racing car. However the results of this conjoint analysis suggest that, as long as the relative performance information is communicated to the consumer, they will not be deterred by the lower peak power figure.

The type of drivetrain was shown to be less important than both acceleration time and price. Again, this would suggest that consumers would not be deterred from buying an alternative drivetrain, as long as the performance and cost were favourable. It is worth noting that while some of the drivetrains received negative average scores, this does not necessarily mean that consumers would be put off by these drivetrains (a result of the way that the utilities were calculated and that they must all sum to zero). The importance of the drivetrain attribute was less than the acceleration time and price attributes, meaning that, again, as long as performance and cost were favourable, consumer may not be deterred from buying these drivetrains. This may be because the consumers put more importance on enjoying the benefits of increased performance, rather on how the performance is achieved.

One reason for the attribute importance for the drivetrain being low may be due to the customers not fully understanding the tradeoffs of the different drivetrains. When the conjoint analysis was carried out (2007), hybrid drivetrains had not been adopted by the majority of manufacturers. As a result there was not a high level of understanding of hybrid drivetrains in the public domain. In motorsport, there was even less understanding of hybrid drivetrains. The only major example of a hybrid drivetrain was the announcement that Formula One could use KERS in two years time (although there was speculation in the media that KERS would not be successful in Formula One [96]).

To investigate price sensitivity, an example hybrid electric vehicle was specified, based on the requirements found, through an interview with Potenza Technology, in chapter 2. This example drivetrain was used to examine the price sensitivity of the hybrid drivetrain compared to a Westfield Sportscars Sport Turbo. In the requirements analysis, Potenza Technology stated that they expected the customer would be willing to pay an additional £8,000 for a hybrid drivetrain that met the project requirements. The analysis carried out using the market simulation tool suggests that approximately 50% of people would purchase the hybrid vehicle at an additional cost of £8,000. However, this only reduced to 45% with a £15,000 additional cost. Therefore, should a cost of £8,000 not be achievable, there is scope to increase the cost to £15,000.

If attempted again, the survey would benefit from expanding the vehicle price range to investigate the price limits in more detail. Also, due to an error in implementation, the survey did not include a power level of 250 BHP. This could also be addressed should the analysis be attempted again.

While the results of the conjoint analysis provide a better indication of price sensitivity than could be achieved with other survey methods, it is worth noting that the importance of price may increase if a customer was actually asked to purchase a vehicle. However, the conjoint analysis has shown that there would be a market for an innovative hybrid drivetrain, with the right performance and price characteristics, in the club motorsport market.

It has also been shown that, to develop an innovative hybrid electric drivetrain for club motorsport, the drivetrain must be designed primarily for performance gains and not for fuel economy gains. Therefore, the drivetrain may not meet the requirements set out for it unless it is designed primarily for performance increase. As one of the main project requirements identified by Potenza Technology was a 0 to 26.8ms^{-1} (0-60mph) acceleration time of three seconds, it makes sense to measure performance in 0 to 26.8ms^{-1} (0-60mph) acceleration time, with the aim of the innovative hybrid electric drivetrain being to achieve a 0 to 26.8ms^{-1} (0-60mph) time as close to 3 seconds as possible.

7.6 Conclusions

This chapter has shown the results of a conjoint analysis into the relationship between performance, price, drivetrain type and fuel economy in the club motorsport industry. Similar to the customer survey, it was seen that the vehicle performance attribute, in terms of 0 to 26.8ms^{-1} (0-60mph) acceleration time, was rated as the most important out of these attributes. However, performance in terms of engine power was the least important. This is due to acceleration being a direct measure of performance and perceived enjoyment and engine power being an indication of the potential performance. It was also shown that price was less important than originally predicted by Potenza Technology. The maximum price Potenza Technology thought a customer would be willing to pay was £8,000. The conjoint analysis has shown that for an extra £15,000, 45% of customers would buy the hybrid version of the Westfield Sportscars Sport Turbo.

These findings prove the viability of a hybrid electric drivetrain for motorsport and that the customer is likely to accept a hybrid electric racing car. The successful implementation of such a drivetrain would represent significant innovation in the club motorsport industry. These findings have therefore opened a new market for the company and the potential significant commercial gain.

A conjoint analysis of this kind has not before been attempted in the club motorsport industry and has been shown to be a powerful tool for understanding customer requirements. As a result, the conjoint analysis, along with the customer survey, were peer reviewed and accepted into The International Journal of Environmental, Cultural, Economic and Social Sustainability [97].

In line with the requirement to identify of the level of customer acceptance of hybrid electric vehicle technologies alongside potential price increases over the standard vehicle, the findings from the conjoint analysis can be used alongside the requirements from Chapter 5, detailed in Table 11. These finding suggest that the maximum price of the drivetrain can be increased from £8,000 to £15,000 and still be commercially viable.

8 VEHICLE SIMULATION TOOL

8.1 Introduction

There are three types of hybrid architectures; series, parallel and combined. To decide on the appropriate hybrid electric vehicle architecture for use in a hybrid Westfield Sportscars Sport Turbo, a method of comparing hybrid architectures was required. As the main objective of this work was to reduce the 0 to $26.8ms^{-1}$ (0-60mph) acceleration time of the system to as near as 3 seconds as possible, this was used as the basis for the architecture comparisons.

It has been shown in the Technology Review chapter that a series hybrid type of hybrid architecture, in a load following configuration, has the potential to increase vehicle performance. However this configuration would not satisfy the requirements of the project because the ICE is not controlled by the driver but by the control system responsible for managing the energy and power flow between the energy storage system and the electric part of the drivetrain. It would also not be possible to retro-fit a series hybrid drivetrain to an existing vehicle as it would require substantial alteration to the vehicle drivetrain and make it difficult to use any of the many engines currently installed in Westfield Sportscars products.

The Technology Review chapter went on to discuss seven different hybrid drivetrain configurations, which were either parallel or combined hybrids. These seven hybrid drivetrain configurations do meet the requirements, assuming system control by the driver can be maintained, by being able to retrofit into an existing vehicle. To compare these drivetrain configurations, a vehicle simulation tool was developed.

The aim of this chapter is to document the development of a vehicle simulation tool that was capable of simulating the range of possible parallel or combined hybrid identified in the literature review, as well as aid the design of other aspects of the drivetrain, such as the energy storage system. The scope of this chapter does not include the simulation and validation of the hybrid electric vehicle specific components. This is discussed in detail in later chapters.

8.2 Methodology

There are two main approaches to vehicle simulation, a forward facing approach or a backward facing approach. A backward facing approach uses a vehicle's desired speed as the input and works backwards through the drivetrain, calculating required torques, powers and efficiencies until an energy requirement from the fuel or electrical energy store has been calculated. Backward facing simulations work well for determining if a vehicle will meet a given drive cycle, but not so well for computing 'best effort' performance or maximum acceleration [98].

Forward facing modelling approaches use a driver model to determine the appropriate throttle (and brake where appropriate) requirements to meet the required vehicle speed. This throttle command or torque request is usually then computed through to the engine/electric motor and on down the drivetrain to the wheels. Forward facing models tend to take longer to compute than backward facing simulations (due to the number of integrations required) [99], but are much better suited to simulating control strategies and maximum acceleration [98].

The aim of the simulation tool was to identify the maximum acceleration given by different hybrid architectures as well as identify the effect of control strategies on the vehicle's acceleration [100]. As forward facing models are well suited to modelling the effects on a vehicle during high acceleration [98, 101], a forward facing simulation approach was taken that incorporated a driver model.

The driver model was designed to optimise the vehicle acceleration profile over a 0 to 26.8ms^{-1} (0-60mph) acceleration event. This was achieved by the driver model being given independent control over the drivetrain components. This means that the post transmission motors and front motors were able to accelerate the vehicle through the gear changes. The driver model was also able to specify different torque requests for the front and rear drivetrains, dependent on the level of grip available.

Figure 28 shows the components that were simulated in the vehicle simulation tool. A detailed battery model was not included in the simulation because, for the purposes of simplifying the comparison of different hybrid architectures, it was assumed that there was sufficient power and energy available to drive the motors. Further information on the design of the simulation tool can be found in Submission 2 of this Engineering Doctorate [6]

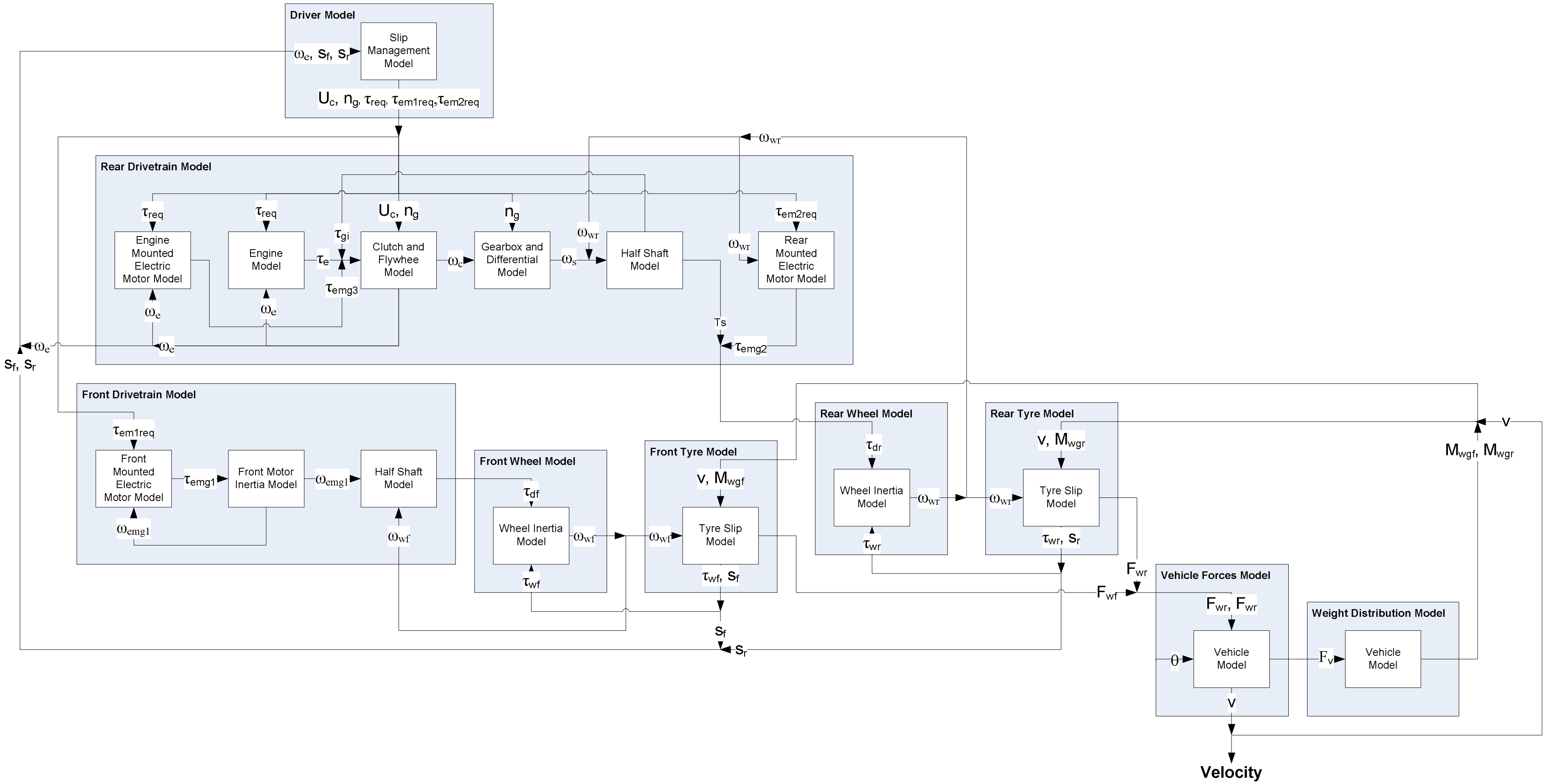


Figure 28. Simulation Tool Architecture Diagram

8.3 Results

The 0 to 26.8ms^{-1} (0-60mph) acceleration of an existing Westfield Sportscars AeroRace racing car, with a Ford Zetec engine, was simulated and the output compared to logged data from a Westfield Sportscars AeroRace used on the track. The data used are shown in Table 19.

Vehicle Parameters	Parameter Value
Total Vehicle Mass (kg)	538
Tyre Rolling Radius (m)	0.2675
Final Drive Ratio	3.92
Gear Ratios	[3.65 1.97 1.37 1 0.82]
Engine Torque (Nm)	[62 80 78 80 87 91 95 98 102 103 104 105 105 106 107 107 108 109 109 110 110 109 106 104 101 94]
Engine Speeds (rads^{-1})	[178 197 216 235 254 273 292 311 330 350 369 388 407 426 445 464 483 502 521 540 559 578 597 616 635 654]

Table 19. Westfield Sportscars AeroRace Simulation Parameters

Figure 29 shows the Westfield AeroRace racing car performing a 0 to 26.8ms^{-1} acceleration event at Brands Hatch race circuit and compares it to a simulated 0 to 26.8ms^{-1} acceleration event. The 0 to 26.8ms^{-1} time of the vehicle at Brand's hatch was 6.33 seconds. The simulated time was 6.43 seconds (a difference in acceleration time of 1.6%). It can be seen that generally the velocity of the two events are close with the main difference being in the early part the acceleration where the simulated driver model appears to achieve a better standing acceleration than the driver from the Brand's hatch data. The traces then follow a similar gradient until the first gear change when the driver from the Brand's Hatch data saw a better acceleration after the first gear change. From that point however, both velocity traces follow each other closely. The maximum difference in velocity at a given point is no more than 0.56ms^{-1} and -1.8ms^{-1}. This is shown in Figure 30.

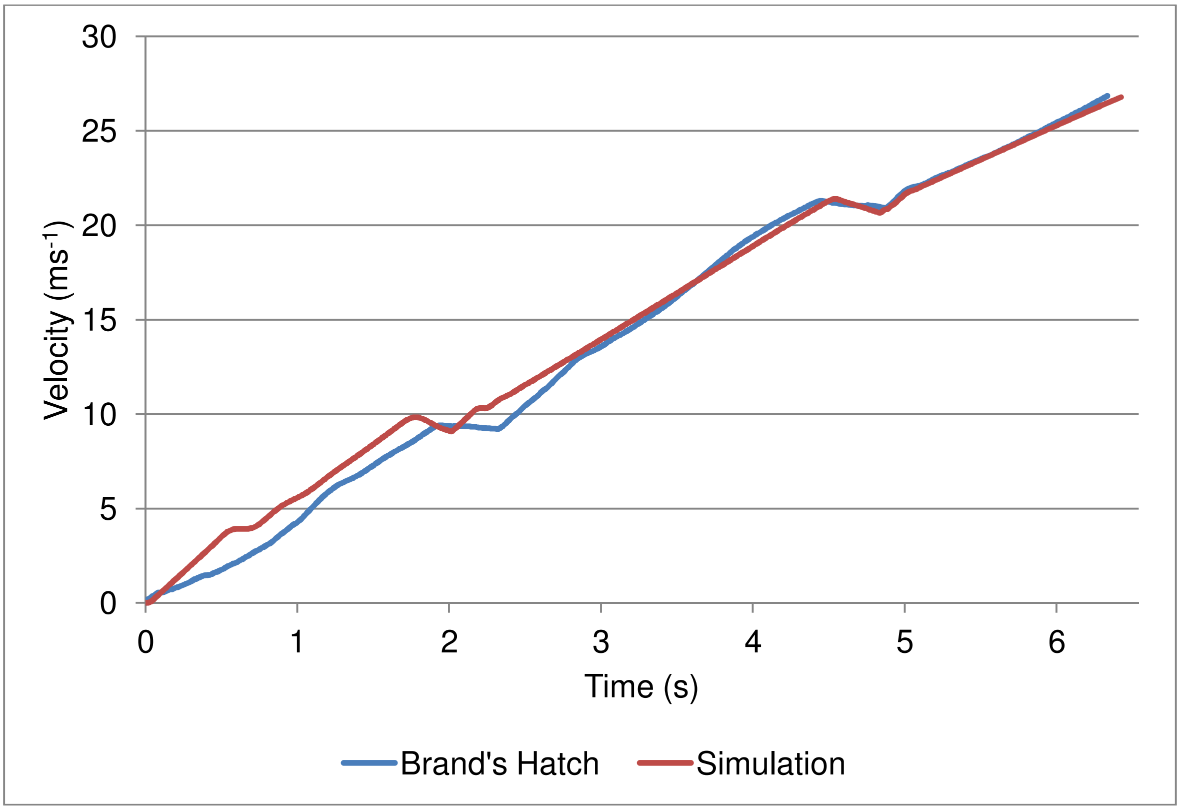


Figure 29. Simulated vs. Brand's Hatch Acceleration of a Westfield Sportscars AeroRace

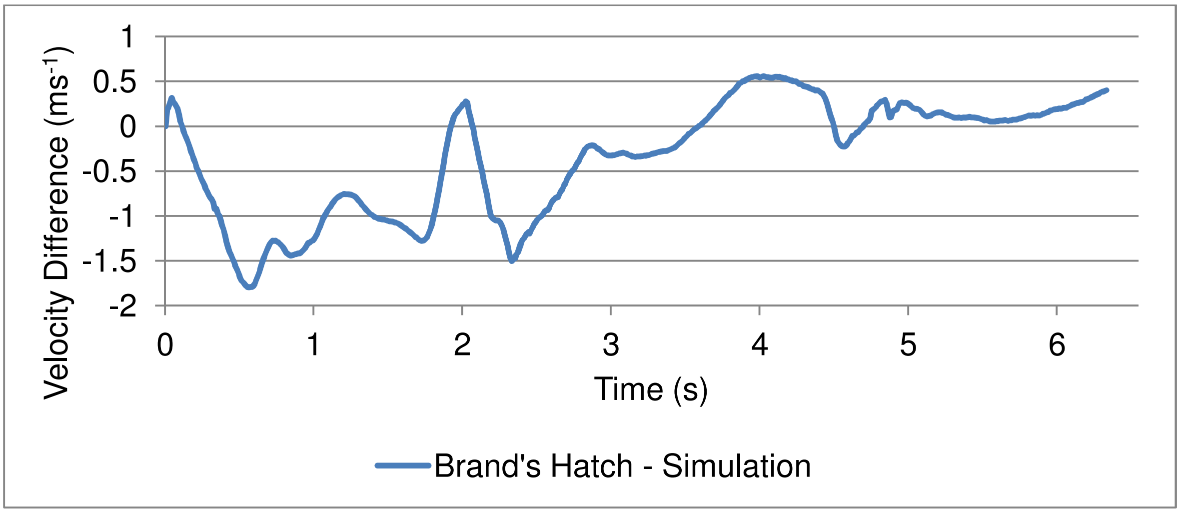


Figure 30. Velocity Difference between Brand's Hatch Data and Simulation

Figure 31 shows the Westfield AeroRace racing car performing a 0 to 26.8ms^{-1} acceleration event at Bruntingthorpe Proving Ground and compares it to the results of the simulation tool. The gear changes were set to change to second and third gears at an engine speed of 520rads^{-1} and 580rads^{-1}. The 0 to 26.8ms^{-1} time of the vehicle at Bruntingthorpe was 6.53 seconds, the simulation achieved a time of 6.52 seconds (a difference in acceleration time of 0.15%). However, examination of the velocities shows that while the time is very close, the way in which the driver in the logged data and the driver model achieved these times was not similar.

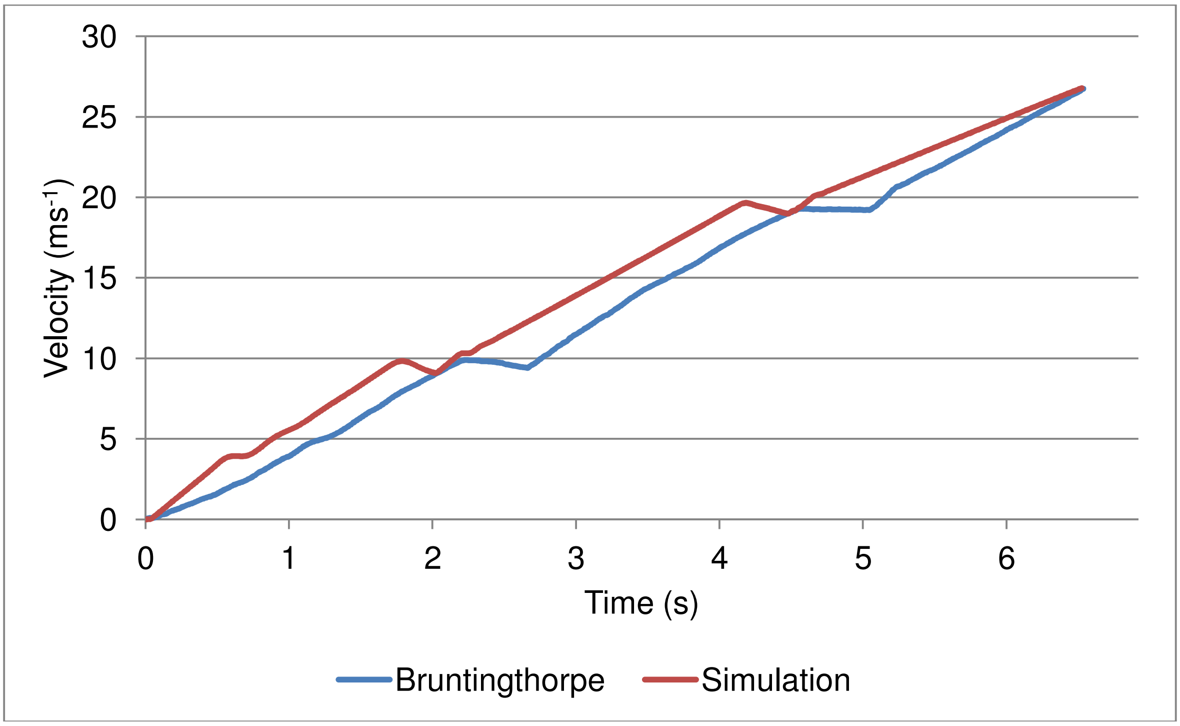


Figure 31. Simulated vs. Bruntingthorpe Acceleration of a Westfield Sportscars AeroRace

Figure 32 shows the simulation trace offset by 0.4s. It can be seen that for the majority of the run the cars accelerated in a very similar way, apart from at the start of the run and at the end of the run. At the start of the run, the simulated driver model showed a better start than the logged data. After the second gear change, the logged data appears to accelerate quicker than the simulated data. It is possible that this is due to there being a downhill section after the start/finish straight at Brands Hatch, or simply that the driver in the logged data was able to get more traction than simulated. The speed difference throughout the trace is shown in Figure 33, where the maximum differences between the traces are $1.36ms^{-1}$ and $-0.94ms^{-1}$.

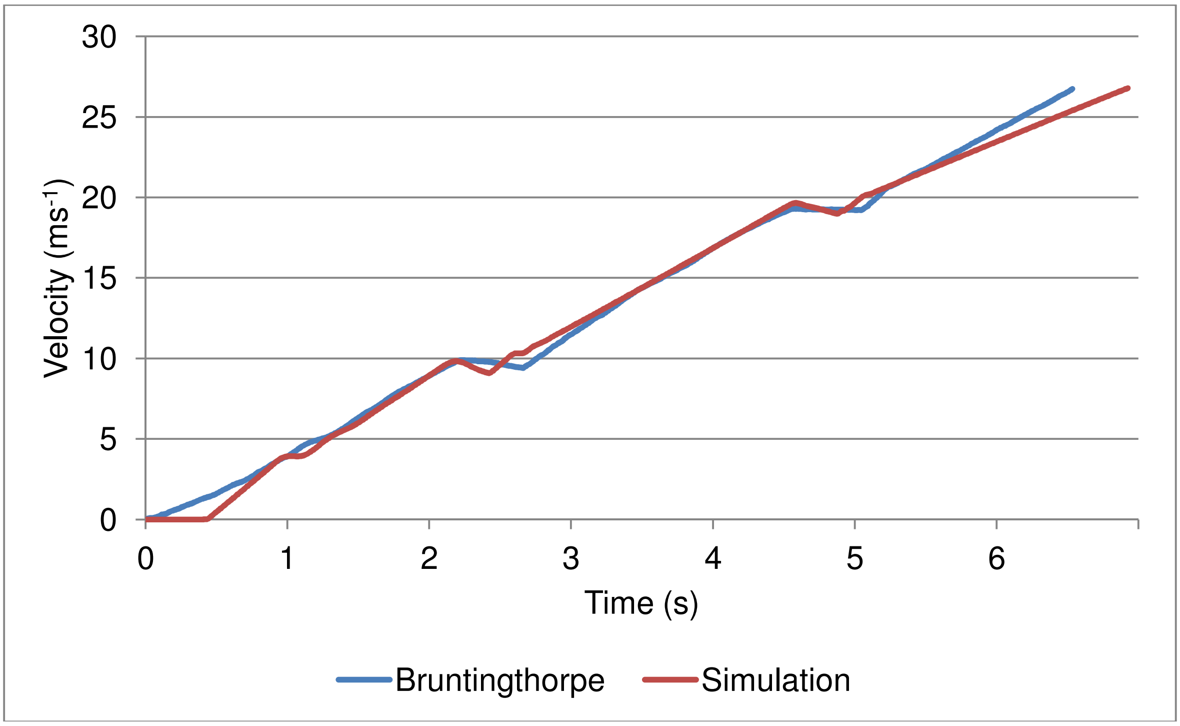


Figure 32. Simulated vs. Bruntingthorpe Acceleration with 0.4s Offset

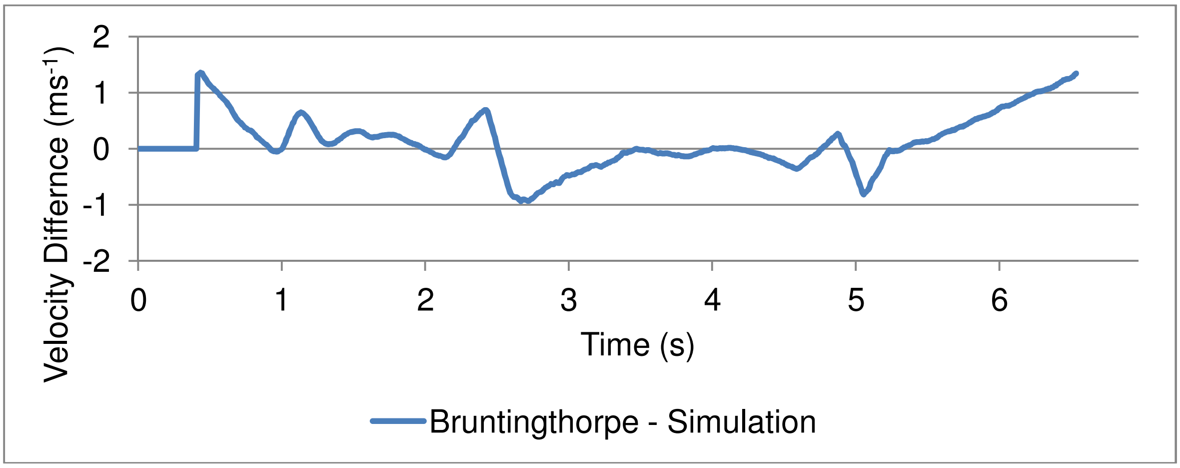


Figure 33. Velocity Difference between Bruntingthorpe Data and Simulation

8.4 Discussion

A vehicle simulation tool has been developed which is capable of simulating the 0 to 26.8ms^{-1} (0-60mph) acceleration time of a Westfield Sportscars racing car. While the simulated velocity does not exactly track the measured velocity, the accuracy of the tool will be sufficient to compare the effect of different drivetrains on a vehicle and give an indication of the 0 to 26.8ms^{-1} (0-60mph) times possible.

The vehicle simulation tool can then be used to simulate hybrid electric vehicle architectures with a choice of simulating motors connected to the engine, rear driveline or front driveline. With these three different motor positions, there are seven possible hybrid electric vehicle architectures, all likely to have a different effect on vehicle 0 to 26.8ms^{-1} (0-60mph) acceleration time.

8.5 Conclusions

While simulation is an established design tool for mainstream vehicle manufacturers, the specialist resources and large software costs restrict its use for most manufacturers of club motorsport and the niche vehicle industry. As a result, design decisions are typically based on engineering experience rather than rigorous investigation. In addition, those tools which are available and can simulate hybrid drivetrains are biased towards simulating their effect on fuel economy. The vehicle simulation tool is able to effectively simulate the effect of different design decisions on hybrid electric vehicle acceleration capabilities, leading to the development of innovative solutions. This tool was required to enable the comparison of different hybrid architectures and motor options, as part of the requirements for this project.

With a lack of hybrid and electric vehicle expertise within the niche vehicle market place, the vehicle simulation tool allows quick and easy comparison of different hybrid electric vehicle designs, suitable for use in the club motorsport industry. This tool, along with how it can be used to determine appropriate hybrid electric vehicle designs for motorsport, was presented at the Hybrid and Eco-Friendly Vehicle Conference in 2008 [102].

9 ARCHITECTURE SELECTION

9.1 Introduction

Seven different types of hybrid architecture have been identified in the literature review as suitable for use in a Westfield Sportscars racing car. Table 20 shows the seven different architectures. The architectures are characterised by the areas within the transmission that electric power is acting on.

Architecture	Pre Transmission Area	Post Transmission Area	Front Transmission Area
Parallel Hybrid	Yes	No	No
Post Transmission Parallel Hybrid	No	Yes	No
Through-the-road Parallel Hybrid	No	No	Yes
Four Wheel Drive Post Transmission Parallel Hybrid	No	Yes	Yes
Post Transmission Combined Hybrid	Yes	Yes	No
Separate Axle Combined Hybrid	Yes	No	Yes
Four Wheel Drive Combined Hybrid	Yes	Yes	Yes

Table 20. Westfield Sportscars Viable Hybrid Architectures

A vehicle simulation tool has been developed which is capable of simulating the 0 to $26.8ms^{-1}$ (0-60mph) acceleration time of a vehicle with the option of using one of the hybrid electric vehicle architectures specified in Table 20. Therefore this tool can be used to determine the 0 to $26.8ms^{-1}$ (0-60mph) acceleration time of the different architectures if used on a Westfield Sportscars Sport Turbo.

The aim of this chapter is to document the result of vehicle simulations, comparing these seven hybrid drivetrain configurations when used in a Westfield Sportscars hybrid electric racing car. The scope of this chapter does not include the selection of motors or energy storage devices as this is covered in later chapters.

9.2 Methodology

Simulations were carried out to understand the effect of different hybrid architectures on a Westfield Sportscars vehicle. The base vehicle simulated was a Westfield Sportscars Sport Turbo. The Sport Turbo is the most popular car that Westfield Sportscars sell. As a result, it is the vehicle platform that Potenza Technology would like the hybrid system to be initially developed for. The parameters for the Westfield Sport Turbo are shown in Table 21.

Vehicle Parameters	Parameter Value
Base Vehicle Mass (kg)	650
Energy Storage Mass (kg)	40
Gearing Mass (kg)	21 when front motor utilised
Motor Mass (kg)	55.9 per motor utilised
Tyre Rolling Radius (m)	0.280
Final Drive Ratio	3.92
Gear Ratios	[3.61 2.08 1.36 1 0.76]
Engine Torque (Nm)	[20 36 46 54 62 75 87 102 117 126 137 149 160 169 180 190 198 205 217 226 235 243 247 258 264 257 254 145 237 217]
Engine Speeds (rads^{-1})	[152 168 183 199 209 225 240 267 283 303 330 356 377 398 413 434 429 476 497 513 529 550 565 581 591 607 618 638 649 660]

Table 21. Westfield Sportscars Sport Turbo Simulation Parameters

To compare the architectures, the same motor was used in all three areas and geared appropriately. The power required to accelerate a mass of 650kg to 26.8ms^{-1} (60mph) in 3 seconds is approximately 78kW [6]. Therefore the motor used was a UQM PowerPhase 75, a motor commonly used in hybrid and electric vehicles [103]. The simulation parameters for the UQM PowerPhase 75 are shown in Table 22. The motors were geared to match the maximum speed of the engine and vehicle where appropriate. The front and rear motors used gear ratios of 4:1, with the engine motor used a gear ratio of 1:1. A differential, with a mass of 21kg, was included in the mass of the front transmission area motor. A mass of 40kg was assumed for an energy storage device, based on the energy storage mass of electrochemical and ultracapacitor systems for power assist hybrids [22].

Attribute	Value
Maximum Power (W)	75000
Maximum Torque (Nm)	240
Maximum Speed (rads^{-1})	837
Weight Including Controller (kg)	55.9

Table 22. Motor Simulation Parameters

9.3 Results

Simulations were carried out to determine the effect of the different architectures on acceleration. The front and rear drivetrains were controlled independently by the driver model to show the theoretical maximum vehicle acceleration. The times that the different architectures achieved a 0 to 26.8ms^{-1} (0-60mph) acceleration event in are shown in Table 23. The corresponding speed traces for the different architectures are shown in Figure 34.

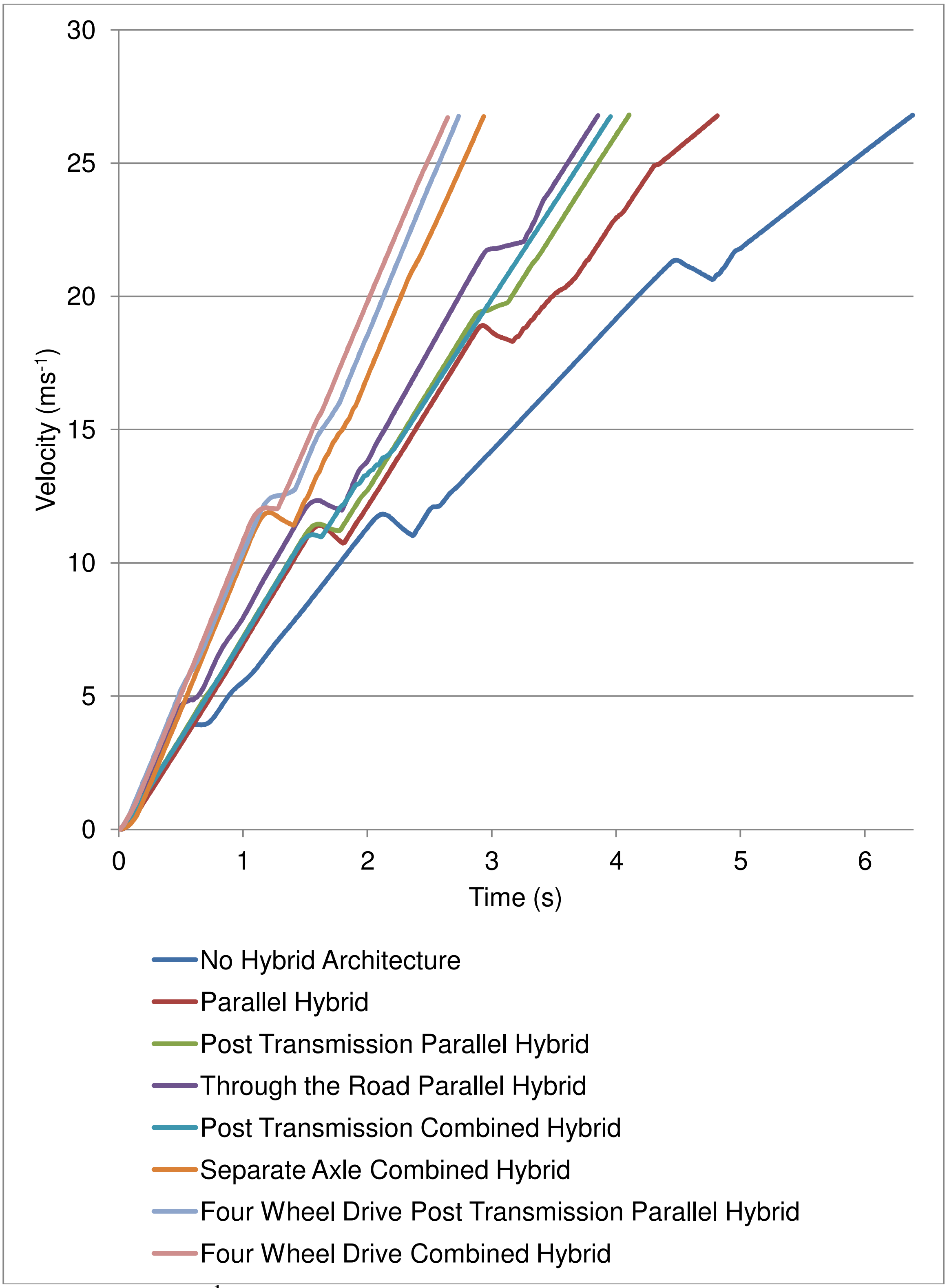


Figure 34. 0 to 26.8ms^{-1} (0-60mph) Acceleration Times

Architecture	**0 – 60 MPH Time (s)**
No Hybrid Architecture	6.38
Parallel Hybrid	4.81
Post Transmission Parallel Hybrid	4.10
Through-the-Road Parallel Hybrid	3.85
Post Transmission Combined Hybrid	3.95
Separate Axle Combined Hybrid	2.93
Four Wheel Drive Post Transmission Parallel Hybrid	2.73
Four Wheel Drive Combined Hybrid	2.64

Table 23. Architecture 0 - 60MPH Times

Figure 34 and Table 23 show that the addition of a hybrid system has the potential to reduce the 0 to 26.8ms^{-1} (0-60mph) time of a Westfield Sportscars Sport Turbo. The largest decrease in acceleration time comes from the four wheel drive combined hybrid architecture which utilises all three motors. It can also be seen that the only architectures which manage a 0 to 26.8ms^{-1} (0-60mph) time of below 3 seconds are the architectures which utilise a front motor alongside another motor.

However, it is not clear how effective the different architectures are at reducing 0 to 26.8ms^{-1} (0-60mph) time, given the different amounts of electrical power employed. For example, the difference in 0 to 26.8ms^{-1} (0-60mph) time between the four wheel drive post transmission parallel hybrid architecture and the four wheel drive combined hybrid architecture is only 0.09s. The difference in these architectures is that the four wheel drive combined hybrid architecture utilises an extra motor attached to the engine. This motor only contributes 0.09s to the reduction in acceleration time. It is therefore important to understand the effectiveness of the different architectures in using electric power in reducing 0 to 26.8ms^{-1} (0-60mph) acceleration time.

The hybridisation factor, as defined in Equation 2 in the literature review, can be used to compare the electrical power utilised in each of the architectures simulated. A way of examining the effectiveness of the different architectures, in terms of the relative benefit to 0 to 26.8ms^{-1} (0-60mph) acceleration time given the additional electrical power employed, is required. To achieve this benefit factor (BF) was created. BF is defined in Equation 9 where t_{HYBRID} and $t_{STANDARD}$ are the 0 to 26.8ms^{-1} (0-60mph) acceleration times of the hybrid architecture and the standard (not hybrid) vehicle respectively. HF is the hybridisation factor of the hybrid architecture. The hybridisation factors and benefit factors for each of the simulated architectures are shown in Table 24.

$$BF = \frac{\left(1 - \left(\frac{t_{HYBRID}}{t_{STANDARD}}\right)\right)}{HF}$$

Equation 9

Architecture	HF	BF
No Hybrid Architecture	N/A	N/A
Parallel Hybrid	0.35	0.70
Post Transmission Parallel Hybrid	0.35	1.02
Through-the-road Parallel Hybrid	0.35	1.13
Post Transmission Combined Hybrid	0.52	0.73
Separate Axle Combined Hybrid	0.52	1.04
Four Wheel Drive Post Transmission Parallel Hybrid	0.52	1.10
Four Wheel Drive Combined Hybrid	0.62	0.95

Table 24. Hybridisation and Benefit Factors of Simulated Architectures

It can be seen from Table 24 that the hybrid architecture that gives the greatest overall benefit, in terms of acceleration for electrical power employed, is the through-the-road parallel hybrid architecture. The separate axle combined hybrid architecture and the four wheel drive post transmission parallel hybrid architecture also provide a large benefit. This is likely to be due to both these hybrid architectures building on the benefits of the through-the-road parallel hybrid architecture by having electric motors driving the front wheels.

9.4 Discussion

Table 25 shows the time decrease, over a standard Westfield Sportscars Sport Turbo, of the three architectures that utilise just one motor. It can be seen that the front motor provides the largest decrease in 0 to 26.8ms^{-1} (0-60mph) acceleration time.

Architecture	Motor Utilised	Time Decrease
Parallel Hybrid	Pre Transmission Motor	1.57
Post Transmission Parallel Hybrid	Post Transmission Motor	2.29
Through-the-road Parallel Hybrid	Front Motor	2.53

Table 25. Time Decrease for each Motor over Standard Vehicle

The pre transmission motor provides the engine with additional torque. This has the benefit of also filling in any gaps in the engine's torque curve, which could provide a smoother engine output. This is an advantage as it could make the car easier to drive, and therefore easier for the driver to go faster.

The post transmission motor provides the same benefits as the pre transmission motor, but has the advantage of being able to drive through the gear changes. Normally there is no driving force during gear changes (it was found to be approximately 0,35s for the Westfield Sportscars race cars) and the cars velocity will not increase during this time. Being able to carry on accelerating through this time will further reduce acceleration time Both the pre transmission and post transmission motors can also take advantage of the extra traction available due to weight transfer from the front to the rear wheels during acceleration, meaning that more force can be transmitted to the road through the rear wheel, increasing acceleration.

However, this weight transfer limits the amount of traction available at the front wheels. Since traction is already limited at the rear wheels by the ICE alone, the transfer of weight to the rear wheels may not contribute a large amount to the reductions in acceleration time. Because there is no force being transferred to the front wheels, there is still more traction available than at the back wheels. Therefore, the motor acting on the front wheels is able to realise the largest decrease in 0 to 26.8ms^{-1} (0-60mph) acceleration time. It is for this reason that the through-the-road parallel hybrid architecture was shown in the simulations to be the most effective hybrid architecture at reducing the 0 to 26.8ms^{-1} (0-60mph) acceleration time of a Westfield Sportscars vehicle. To implement this architecture the appropriate motors must be analysed, a suitable battery system designed and a method of system control developed.

The Benefit Factor of the Four Wheel Drive Post Transmission Parallel Hybrid was only slightly smaller than the benefit factor of the Through-the-road Parallel Hybrid. However the Four Wheel Drive Post Transmission Parallel Hybrid utilises three times as much electric motor power. Whilst the theoretical acceleration time of the Four Wheel Drive Post Transmission Parallel Hybrid is lower than the Through-the-road Parallel Hybrid, it is unlikely to be possible to fit the required amount of electric motor power into the Westfield Sportscars SE chassis and also meet the other project requirements.

9.5 Conclusions

This chapter has shown the effect of different hybrid architectures on the acceleration of a Westfield Sportscars racing car. Whilst three of the architectures were able to see an acceleration of below 3 seconds, it did not represent the optimum use of employed electrical power.

To investigate the effectiveness of the electrical power on acceleration, the new method of comparing the effectiveness of hybrid architectures in improving the performance of a vehicle, benefit factor, was defined. This new method was used to find that a through-the-road parallel hybrid architecture represented a greater benefit for the electrical power employed on the vehicle, accelerating the vehicle from 0 to $26.8ms^{-1}$ (0-60mph) in 3.819s, using a third of the electrical power of the four wheel drive combined hybrid. Had the benefit factor calculation method not been utilised, a four wheel drive combined hybrid may have been chosen as it gave showed the quickest 0 to $26.8ms^{-1}$ (0-60mph) acceleration time. However, this would have come at the significant cost of two extra motors per vehicle.

Based on the benefit factor calculation, the through the road parallel hybrid architecture has been shown to provide the greatest benefit in acceleration given the electrical power employed and therefore a through the road architecture will be utilised in the hybrid Westfield Sportscars racing car.

One of the aims of developing a hybrid electric vehicle for use in a Westfield Sportscars racing car, was to contribute to innovation within the motorsport industry. The benefit factor calculation is an example of an innovation that could assist in developing hybrid electric drivetrains for motorsport in the future.

10 ELECTRIC MOTOR SELECTION

10.1 Introduction

The first step in developing a through-the-road parallel hybrid drivetrain is to determine the suitable electric motor technology. The analysis of suitable electric motors can be carried out in two ways.

- Investigate the theoretical optimum motor characteristics and use this information to design, build and test a bespoke electric motor for use in the drivetrain
- Investigate the effect of currently available electric motors, leading to the selection of one of these electric motors for use in the drivetrain.

It is not feasible for a company the size of Potenza Technology to design, build and test a bespoke electric motor for use in this vehicle. For example, YASA motors employs a at least 15 people and received an initial £1.45m investment to aid development of the motor [104]. In comparison Potenza Technology currently employ 5 people, wish to remain privately owned and do not wish to undertake the production of electric motors. Therefore only the effects of using currently available electric motors were investigated.

The aim of this chapter is to identify the motor technology that will be used in the drivetrain for a hybrid Westfield Sportscars Sport Turbo. This was achieved through an investigation into the effect of different motors on the 0 to 26.8ms^{-1} (0-60mph) acceleration time of a hybrid Westfield Sportscars Sport Turbo.

Whilst there are many types of motor technology available, the scope of this chapter does not include an investigation into the suitability of motor technology in terms of motor type (permanent magnet, induction etc). This is because, to measure performance, the torque, power and weight of the motor is most significant. Other issues, such as packaging, cost, and availability, are examined in later chapters.

10.2 Methodology

The simulation tool was run, using the vehicle parameters for the Sport Turbo, as shown in Table 21. The architecture was set as a through-the-road parallel hybrid architecture with the parameters of the motor technology used at the front wheels varied to represent electric motors currently available. A gearing was applied to each motor to allow it to operate within its operating speed range throughout the vehicle speed range. A mass of 40kg was used to represent a battery system, capable of providing sufficient electrical power to the motor. A mass of 21kg was used to represent the mass of a differential, where relevant. This is the same mass as the differential currently used in the Westfield Sportscars Sport Turbo. Where there is one motor running through a differential, a mass of 21kg was added to the mass of the vehicle. Where there is more than one motor, if gearing is required, a mass of 21kg was also added to represent the required gearbox. If no gearing is required, and direct drive to the wheels is possible, then no additional gearbox/differential mass was added. The vehicle parameters used are shown in Table 26.

Vehicle Parameters	**Parameter Value**
Base Vehicle Mass (kg)	650
Energy Storage Mass (kg)	40
Gearing Mass (kg)	21 (if required)
Motor Mass (kg)	Varied
Tyre Rolling Radius (m)	0.280
Final Drive Ratio	3.92
Gear Ratios	[3.61 2.08 1.36 1 0.76]
Engine Torque (Nm)	[20 36 46 54 62 75 87 102 117 126 137 149 160 169 180 190 198 205 217 226 235 243 247 258 264 257 254 145 237 217]
Engine Speeds (rads^{-1})	[152 168 183 199 209 225 240 267 283 303 330 356 377 398 413 434 429 476 497 513 529 550 565 581 591 607 618 638 649 660]

Table 26. Vehicle Parameters for Motor Simulations

10.3 Results

The simulation results of using 48 different commercially available motor configurations are shown in Table 27.

Manufacturer	**Motor Name**	**Power (kW)**	**Torque (Nm)**	**Speed (rads^{-1})**	**Weight (kg)**	**Gear**	**Motors**	**0 to 26.8ms^{-1} time (s)**
UQM	Powerphase 75	75	240	838	56	4	1	3.85
Enova	EDM60	60	159	1047	91	5	1	4.04
Enova	EDM90	90	239	1047	100	5	1	3.77
Siemens	ACW-80-4	38	60	1309	37	6.25	1	4.75
Siemens	ACW-80-4	38	60	1309	37	6.25	2	4.01
Siemens	1FV5104-WS09	44	75	670	54	3.2	1	5.41
Siemens	1FV5104-WS09	44	75	670	54	3.2	2	4.81
Siemens	1LH5118	49	123	1047	57	5	1	4.22
Siemens	1LH5118	49	123	1047	57	5	2	3.80
Siemens	1PV5135WS14	78	190	1016	106	4.85	1	3.94
Siemens	1PV5135WS18	78	260	1016	106	4.85	1	3.77
Brusa	ASM 810	64	300	733	83	3.5	1	3.81
MES DEA	MES 150 - 100	12	30	942	49	4.5	1	6.03
MES DEA	MES 150 - 100	12	30	942	49	4.5	2	5.54
MES DEA	MES 200-75	9	30	942	49	4.5	1	6.06
MES DEA	MES 200-75	9	30	942	49	4.5	2	5.59
MES DEA	MES 200-150	18	60	942	60	4.5	1	5.36
MES DEA	MES 200-150	18	60	942	60	4.5	2	4.75
MES DEA	MES 200-175	21	70	942	64	4.5	1	5.20
MES DEA	MES 200-175	21	70	942	64	4.5	2	4.56
MES DEA	MES 200-250	30	100	942	76	4.5	1	4.75
Lynx Motion	E225	6	10	628	23	3	1	6.68
Lynx Motion	E225	6	10	628	23	3	2	6.61
Lynx Motion	E813	130	450	288	310	1.375	1	5.33
Brusa	ASM6.17.12	54	192	1152	49	5.5	1	3.73
Brusa	ASM6.17.12	54	192	1152	49	5.5	2	3.73
Brusa	ASM8.24.10	53	530	628	68	3	1	3.73
Brusa	HSM6.17.12	70	223	1152	51	5.5	1	3.69
Brusa	HSM6.17.12	70	223	1152	51	5.5	2	3.64

Manufacturer	**Motor Name**	**Power (kW)**	**Torque (Nm)**	**Speed (rads^{-1})**	**Weight (kg)**	**Gear**	**Motors**	**0 to 26.8ms^{-1} time (s)**
E-Traction	e-Traction SM350/1	32	600	262	85	1.25	1	4.32
Azure Dynamics	AC24	43	74	1257	53	6	1	4.63
Azure Dynamics	AC24	43	74	1257	53	6	2	3.96
Azure Dynamics	AC90/DMOC645	97	665	524	217	2.5	1	3.87
Azure Dynamics	AC55/DMOC445	59	280	838	121	4	1	3.89
Ansaldo	A2H182B	15	80	733	44	3.5	1	5.28
Ansaldo	A2H182B	15	80	733	44	3.5	2	4.61
Ansaldo	A1H185C	30	130	1047	58	5	1	4.34
Ansaldo	A1H185C	30	130	1047	58	5	2	3.81
Raser	Symetron P-2	373	570	654	67	3.125	1	3.70
AC Propulsion	AC-150	220	150	1152	80	5.5	1	3.96
Perm Motor	PMS156W	32	51	628	44	3	2	5.31
Protean Electric	HPD40	120	750	209	25	1	1	3.86
Zytec	IDT 120-55	55	120	1257	60	6	1	4.02
NetGain	WarP 9	52	157	576	79	2.75	1	4.77
Lynch	D135RAG	34	80	419	11	2	1	5.57
Lynch	D135RAG	34	80	419	11	2	2	4.88
Lynch	D135RAG	34	80	419	11	2	4	4.07
Oxford YASA	YASA-750	75	500	209	30	1	2	3.73

Table 27. 0 to 26.8ms^{-1} (0-60mph) Acceleration Times for Different Electric Motors

10.4 Discussion

The results of simulating 48 different motor configurations in a through-the-road parallel hybrid architecture, implemented in a Westfield Sportscars Sport Turbo, are shown in Table 27. It can be seen that the range of 0 to 26.8ms^{-1} (0-60mph) acceleration times varied from between 3.64 and 6.068 seconds. The ten motors able to provide the fastest vehicle acceleration are shown in Table 28. As the exact accuracy of the simulation with a hybrid drivetrain is unknown, these motors were also compared against each other based on the packaging, cost and availability requirements of the project.

Manufacturer	Motor	Gearing	Motors	0 to 26.8ms^{-1} (s)
Brusa	HSM6.17.12	Yes	1	3.64
Raser	Symetron P-2	Yes	1	3.7
Oxford YASA	YASA Motor	No	2	3.73
Brusa	ASM6.17.12	Yes	1	3.73
Brusa	ASM8.24.10	Yes	1	3.73
Enova	EDM90	Yes	1	3.77
Siemens	1PV5135WS18	Yes	1	3.77
Siemens	1LH5118	Yes	2	3.8
Brusa	ASM 810	Yes	1	3.81
Ansaldo	A1H185C	Yes	2	3.81

Table 28. Potential Motor Options

One requirement of this project was to develop a hybrid electric drivetrain that could be packaged into the most popular Westfield Sportscars' vehicle, the Sports Turbo. Whilst not the quickest, Oxford YASA Motors' (OYM), YASA-750 is the easiest motor to package. It will fit into the space forward of the engine and is also the only motor amongst these ten that is a 'pancake' motor and therefore the two will package easily. Although there are other quicker motors, these require a differential to also be packaged which would be difficult to accommodate in the chassis and would introduce further expense.

Another requirement was to provide the drivetrain at no greater than £8-15,000 extra cost to the customer (as discussed in Chapter 7). Although the quickest, the Brusa motors were the most expensive in production. The Siemens and Ansaldo were the cheapest. At the time of the tests, the Enova motors and the YASA-750 motors were only available as prototypes; however, their costs were expected by the manufacturers to fall in line with the Siemens and the Ansaldo once in production. For the YASA-750 motors these costs could be expected to fall further as Westfield Sportscars used these motors for their electric race car.

The Brusa and Ansaldo motors were the most readily available as they were in production at the time. However, these suppliers are based outside of the UK and as such it was perceived that support may have been an issue with these motors. During this work, it was discovered that the Siemens motors were no longer manufactured, and would not be suitable for use. The Raser motor was a prototype that was subsequently never taken forward into production. While, at the time of the investigation, the YASA-750 motor was still a prototype, the UK base and clear production intents made it the most available motor.

10.5 Conclusions

This chapter has documented the comparisons, in terms of 0 to 26.8ms^{-1} (0-60mph) acceleration time, of 48 different motor choices for a hybrid Westfield Sportscars Sport Turbo. Comparing the quickest 10 motors against the packaging, cost and availability requirements, the motor from Oxford YASA Motors was identified as the motor most suitable for use in this hybrid drivetrain.

As well as resulting in one of the shortest 0 to 26.8ms^{-1} (0-60mph) acceleration times, this motor system does not require the use of a differential or extra gearing, reducing the potential cost and complexity of a hybrid drivetrain based on this system. The work carried out using the simulation tool has determined the choice of hybrid electric architecture and electric motor. With this objective met, the energy and power requirements of this motor can be used to determine an appropriate energy storage system.

11 ENERGY STORAGE SYSTEM SELECTION

11.1 Introduction

To power a hybrid electric drivetrain installed in a Westfield Sportscars Sport Turbo, an energy storage system is required. The energy storage system will need to store enough energy to meet the demands of system. In addition, the energy storage system must be able to release the energy at the required rate (i.e. the power of the system) to meet the demands of the drivetrain.

The literature review has identified that there are two energy storage technologies that may be appropriate for use in a lightweight sports car. These were ultracapacitor based systems and electrochemical batteries with lithium ion cells. Only lithium ion cells were investigated and not other types of electrochemical systems, such as Nickel Metal Hydride (NiMH), as the drivetrain requires energy storage systems with very high specific power and high power lithium ion systems have higher specific power than NIMH systems [16]. Furthermore, as the project progressed, the Westfield Electric racing car was designed, utilising a Lithium Ion battery pack. It was made clear by the supporting company that if an electrochemical system was used, it should be of similar technology to the electric vehicle, in terms of chemistry (Lithium Ion), but would probably require a different cell because the power/energy requirements of the hybrid and electric vehicles will be different.

The aim of this chapter is to investigate the energy storage systems that are suitable for use in a Westfield Sportscars Hybrid Electric Racing Car, leading to the identification of a suitable energy storage technology. The scope of the chapter does not include battery chemistries that were not available at the time the investigation was carried out (2008). Whilst new chemistries and cells are now available, the investigation represents the state of the art at the time, on which subsequent decisions were based.

11.2 Methodology

The energy storage system selection was carried out by comparing the suitability of different ultracapacitor systems and different lithium ion battery systems in terms of energy storage capacity and mass.

The data for each technology were gathered from available literature and datasheets. From this an example system configuration was determined, based on the power requirements of the hybrid system. A total system power of 80kW was used, representing the maximum constant power of the Oxford YASA Motors dual motor system. The details for each cell used, can be found in Submission 4 of this Engineering Doctorate [7].

The peak power of the Oxford YASA Motors dual motor system is 150kW (75kW each), and this peak power was used when comparing motors. However, constant power was used to compare energy storage systems, due to the inconsistent way in which cell manufacturers quote cell peak currents. Therefore, the constant power rating of the Oxford YASA motor system, 80kW (40kW each), was used to size the energy storage systems.

Constant power of the cells was used as there is not a consistent definition of cell peak current. For example, some cell manufacturers quote the short circuit current of the cell as the peak current and some manufacturers quote the maximum current that the cell can sustain for 10 seconds as the peak current. In addition, the voltage of the cell at these currents is not included in cell datasheets. At high current the voltage of the cell will drop, and this voltage is required to determine the cell power at that current level.

11.2.1 Ultracapacitor Systems

For the ultracapacitor system, a number of different sized ultracapacitors from the same range were used to compare the effect of different size ultracapacitors. Due to the exponential discharge curve of ultracapacitors, as shown in Figure 35, a DC/DC converter was included within the example energy storage system configuration. The DC/DC converter used was a Brusa BDC412, whose characteristics are shown Table 29.

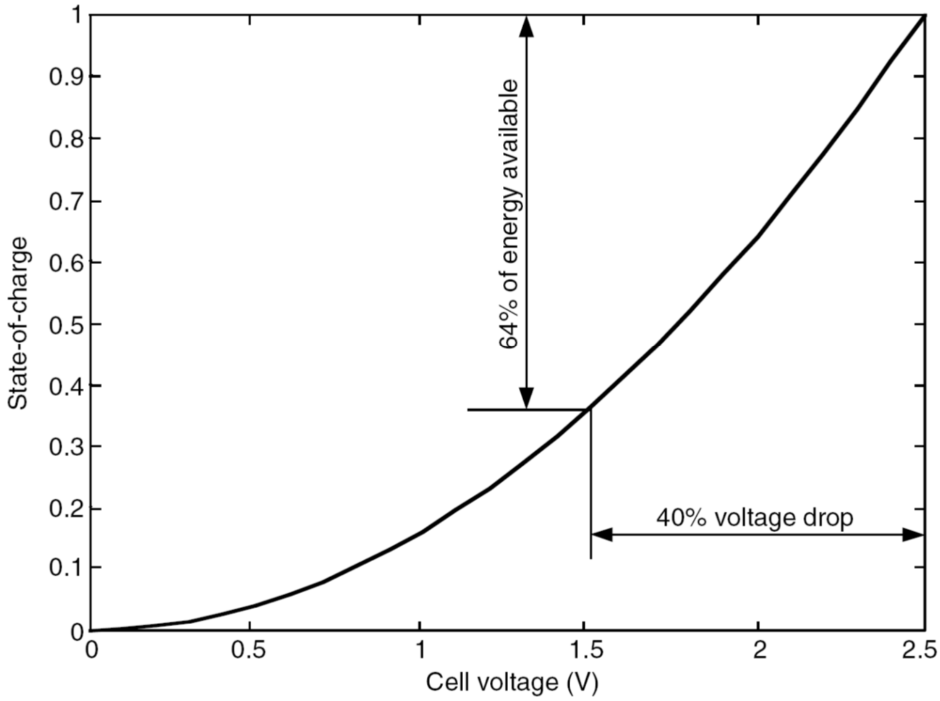


Figure 35. Typical Ultracapacitor State of Charge vs. Cell Voltage [12]

High Side Voltage Range	125-425V
Low Side Voltage Range	100-400V
Maximum Low Side Current	150A
Efficiency	97-99%
Weight	10.25kg

Table 29. Brusa BDC412 DC/DC Converter Characteristics

Using the power requirements of the electric motors and the voltage characteristics of the Brusa BDC412 DC/DC converter, the requirements for the ultracapacitor system can be defined. The maximum system voltage (V_{maxUC}) and minimum system voltages (V_{minUC}) are defined by the low side voltage range of the Brusa BDC412 DC/DC converter. The system power (P_{UC}) is defined by the constant motor power (P_{motor}) and the efficiency of the DC/DC converter (η_{DCDC}), this is shown in Equation 10. For η_{DCDC}, the inverter efficiency, the middle of the quoted efficiency range was used, 0.98. The average current (I_{avgUC}) that the system will see is defined by Equation 11.

$$P_{UC} = \frac{P_{motor}}{\eta_{DCDC}}$$

Equation 10

$$I_{avgUC} = \frac{\left(\frac{P_{UC}}{V_{minUC}}\right) + \left(\frac{P_{UC}}{V_{maxUC}}\right)}{2}$$

Equation 11

In order to compare the different size ultracapacitors, the number of ultracapacitors in parallel (n_{cp}) was kept to one. The number of ultracapacitors in series is defined by Equation 12, where V_{cell} is the maximum cell voltage. For the ultracapacitors used, V_{cell} is 2.5V, meaning that, in the example ultracapacitor configuration, there will be 160 cells in series. The ultracapacitor system requirements are shown in Table 30

$$n_{cs} = \frac{V_{maxUC}}{V_{cell}}$$

Equation 12

System Requirement	**Value**
Maximum System Voltage V_{maxUC} (V)	400
Minimum System Voltage V_{minUC} (V)	100
Ultracapacitor System Power P_{UC} (W)	81632
Ultracapacitor Average Current $_{avgUC}$ (A)	510
Number of Ultracapacitors in Series n_{cs}	160
Number of Ultracapacitors in Parallel n_{cp}	1

Table 30. Ultracapacitor System Requirements

Five ultracapacitor systems were compared, each with different cell resistances (R_{cell}), cell capacitances (C_{cell}) and masses (m_{cellUC}). Using this information it was possible to calculate, for each system, the capacitance (C_{stack}), the resistance (R_{stack}), the maximum boost time (t_{UC}) and the total cell mass ($m_{totalUC}$) using Equation 13, Equation 14, Equation 15 and Equation 16. The information from these comparisons was then used to determine the suitability of the different systems for use in a hybrid drivetrain used in a club motorsport vehicle, in terms of system mass and boost time available.

$$C_{stack} = C_{cell}\frac{n_{cp}}{n_{cs}}$$

Equation 13

$$R_{stack} = R_{cell}\frac{n_{cs}}{n_{cp}}$$

Equation 14

$$t_{UC} = \frac{C_{stack}(V_{maxUC} - V_{minUC} - (I_{avgUC} \times R_{stack}))}{I_{avgUC}}$$

Equation 15

$$m_{totalUC} = m_{cellUC} \times n_{cs} \times n_{cp}$$

Equation 16

11.2.2 Lithium Ion Battery Systems

The investigation into the lithium ion cell systems was carried out by comparing eight high power cells in example configurations that gave a constant battery power ($P_{battery}$) of 80kW. Each cell was characterised by its nominal voltage (V_{nom}), maximum constant current ($I_{constmax}$), nominal charge capacity (Q_{nom}) measured in Ah, mass (m_{cell}) and maximum charging current ($I_{chargemax}$). Unlike ultracapacitors, lithium ion cells have different charge and discharge characteristics.

Using this information it was possible to calculate, for each system, the number of cells required to meet the battery power (n_c), total cell mass ($m_{totalcell}$), available discharge time ($t_{discharge}$) and charge time (t_{charge}) in minutes using Equation 17, Equation 18, Equation 19, and Equation 20.

$$n_c = \frac{P_{battery}}{I_{constmax} \times V_{nom}}$$

Equation 17

$$m_{totalcell} = m_{cell} \times n_c$$

Equation 18

$$t_{discharge} = 3600\frac{Q_{nom} \times V_{nom} \times n_c}{P_{battery}}$$

Equation 19

$$t_{charge} = \frac{Q_{nom}}{I_{chargemax}} \times 60$$

Equation 20

Equation 20 was used as an indication of charging time for comparative purposes only. To fully charge a cell, a cycle of constant current charging is required, followed by a period of constant voltage charging, as shown in Figure 36. Equation 20 gives an indication of the time, in minutes, required to put the cell capacity back into the cell assuming constant current charging. Exact charging times are dependent on the exact characteristics of each cell, for which data are not included on the datasheets.

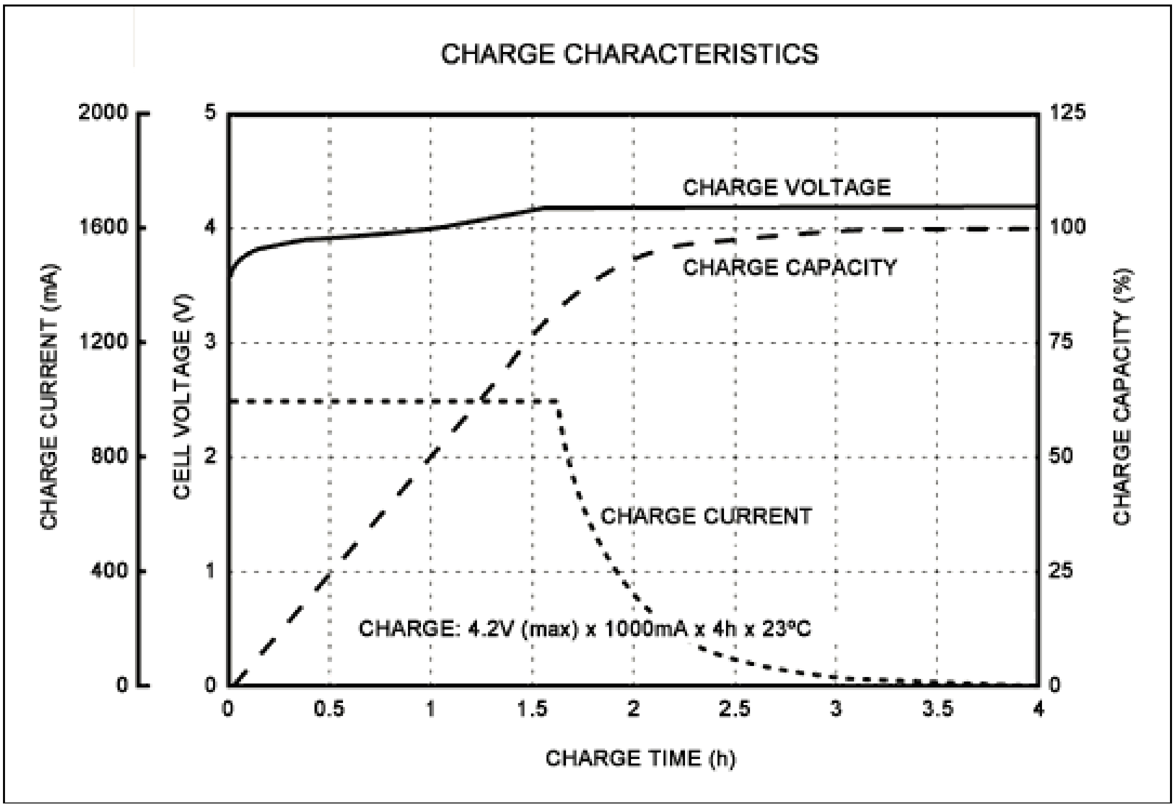


Figure 36 - Constant Current / Constant Voltage Charging [105]

11.3 Results

11.3.1 Ultracapacitor Systems

Table 31 shows the boost time available (t_{UC}) and the total cell mass ($m_{totalUC}$) for five different ultracapacitor configurations. It can be seen that an ultracapacitor solution would be able to provide sufficient boost to accelerate a hybrid electric Westfield Sportscars Sport Turbo from 0 to 26.8ms^{-1} (0-60mph) in 4 seconds. However, the total length of time for the boost will be limited by the type of cell used.

	UC Cell 1	UC Cell 2	UC Cell 3	UC Cell 4	UC Cell 5
Cell Capacity C_{cell} (F)	650	1200	1500	2000	3000
Cell Resistance R_{cell} (Ω)	0.0008	0.00058	0.00047	0.00035	0.00029
Mass m_{cellUC} (kg)	0.20	0.30	0.32	0.40	0.55
Stack Capacity C_{stack} (F)	4.0625	7.5	9.375	12.5	18.75
Stack Resistance R_{stack} (Ω)	0.128	0.0928	0.0752	0.056	0.0464
Discharge Time t_{UC} (s)	1.87	3.71	4.81	6.65	10.15
Total Mass $m_{totalUC}$ (kg)	32	48	51.2	64	88

Table 31. Ultracapacitor System Comparisons

11.3.2 Lithium Ion Battery Systems

Table 32 shows the number of cells (n_c), total cell mass ($m_{totalcell}$), discharge time ($t_{discharge}$) in seconds and charge time (t_{charge}) in minutes. It can be seen that there are two systems that can provide a power of 80kW and have a low total mass. These are the systems using Cell A and Cell D.

	Cell A	Cell B	Cell C	Cell D	Cell E	Cell F	Cell G	Cell H
Nominal Voltage V_{nom} (V)	3.3	2.3	3.2	3.65	3.6	3.3	3.2	3.2
Discharge Current $I_{constmax}$ (A)	70	110	42	350	100	120	2.7	20
Nominal Capacity Q_{nom} (Ah)	2.3	11	2.6	6	7	40	1.35	2.4
Cell Mass m_{cell} (kg)	0.07	0.366	0.082	0.34	0.37	1.6	0.04	0.084
Battery Power $P_{battery}$ (W)	80000	80000	80000	80000	80000	80000	80000	80000
Charge Current $I_{chargemax}$ (A)	10	66	5	6	7	120	0.675	1.2
Number of Cells n_c	346	316	595	63	222	202	9259	1250
Total Mass $m_{totalcell}$ (kg)	24	116	49	21	82	323	370	105
discharge Time $t_{discharge}$ (s)	118	360	223	62	252	1200	1800	432
Charge Time t_{charge} (min)	14	10	31	60	60	20	120	120

Table 32. Lithium Ion System Comparisons

11.4 Discussion

Ultracapacitor systems are able to provide the power for the duration of the required boost. As an example, the system based on UC Cell 2 could provide 3.71 seconds of boost, potentially enough for a single 0 to $26.8ms^{-1}$ (0-60mph) acceleration event. However at the end of this event, the energy in the ultracapacitor system will have been depleted and will need recharging. The weight of the cells in this system is 48kg. With the Brusa BDC412 DC/DC converter, this mass increases to 58.25kg. In comparison, it has been shown that there are two lithium ion based systems that can provide sufficient power at less than half the mass.

It was shown in the literature review that the specific power of ultracapacitors is greater than the specific power of lithium ion systems. The examples shown in this chapter contradict this and suggest that, for this application, lithium ion batteries are able to meet the power demands for the system and provide a much larger amount of energy in a much reduced mass. Therefore, whilst ultracapacitors may have a higher peak power rating, to sustain that power, even for a few seconds, the mass of the ultracapacitor system has to increase to the point that the mass of the system is greater than the lithium ion systems. Ultracapacitors do have the advantage that they can harness more regenerative braking energy, due to their high charging rates, this ability, however, comes at a substantial weight penalty. To reduce the effect on vehicle dynamics, the mass of the system should be minimised.

The lithium ion systems based on Cell A and Cell D have very similar cell masses to each other, at 24kg and 21kg respectively. The system based on Cell A has almost double the capacity of the system based on Cell D. This additional capacity allows the system to sustain an 80kW discharge for 118s, compared to 62 seconds for the system based on Cell D. This extra energy could be utilised to during the race to provide additional durations of boost, increasing performance on the track.

In addition, the number of cells required for the system based on Cell D is only 63. At a nominal voltage of 3.65V, this means the system voltage will be only 229.95V. The nominal voltage requirements for the Oxford YASA Motors dual motor system (using a Semikron inverter) is 400V. This means that, if the system based on Cell D was utilised, additional cells will be required to meet the required nominal voltage for the motors, making the Cell D system heavier. In comparison, Cell A uses many more cells, giving a theoretical maximum nominal voltage of 1141.8V, however, this voltage could be reduced to closer to 400V by connecting the cells in parallel. This is discussed in more detail in Chapter 13.

Furthermore, the maximum charge current of the system based on Cell A is higher than that of the system based on Cell D. This makes the charge time significantly shorter for the Cell A system and also allows scope to introduce regenerative braking.

Although not a requirement of this project, an advantage of using the lithium ion system over the ultracapacitor system is that it could meet the hybrid electric vehicle qualifying regulations for the 24 Heures du Mans by being able to propel the car at 60km/h along a pit lane (400m). Using the values for coefficient of drag, cross sectional area and wheel diameter identified in Submission 3 of this Engineering Doctorate [6], a Westfield Sportscars Sport Turbo requires approximately 11kW of power to overcome aerodynamic forces at 60km/h. To travel 400m at 60km/h requires at least 24s discharge time. The maximum discharge time of the battery based on Cell A is 118s. With discharge times of less than 24 seconds, the ultracapacitor systems would not be able to achieve this.

It has therefore been shown that the system that comes closest to meeting the requirements of a hybrid electric Westfield Sportscars racing car is the lithium ion system based on Cell A. Ultracapacitor based systems are simply too heavy and are not able to store as much energy as some of the lithium ion based systems.

The choice of energy storage system was based on the determining the best system to achieve the primary design target, a low 0 to 26.8ms^{-1} (0-60mph) acceleration. No consideration on system operation was taken into account at this stage as there are no predetermined series regulations that the drivetrain must meet. This presented an opportunity for innovation in the control of the system.

11.5 Conclusions

Through an investigation into energy storage systems appropriate for use in a Westfield Sportscars Hybrid Electric Racing Car, an appropriate energy storage system has been identified which is able to meet the acceleration requirements of the drivetrain. Of the systems compared, Lithium Ion Cell A has been identified that is able to produce the required power for the Oxford YASA Motors dual motor system, with a total cell mass of 24 kg and total boost time of 118s at 80kW power and will therefore be used to produce a battery pack for the hybrid drivetrain to enable the system to be fully designed and integrated within a prototype hybrid electric Westfield Sportscars racing car. It has also been shown that ultracapacitors, contrary to what the literature has suggested, are not a viable option as their weight is far in excess of lithium ion systems, even when a short boost is required.

It has been shown that the system based on Cell A has a mix of high discharge rates, high energy content, but poor charging characteristics. Therefore a primarily regenerative system, such as used in Formula One and the 24 Heures du Mans would not be appropriate. A more appropriate solution, given the cell characteristics, would be to have an energy storage device that was charged before an event. The driver would then have the choice of how and when a limited number of boost events could be used. A system that operates in this way would be new and, if successfully developed, would be innovative in both the motorsport industry and the wider automotive industry, meeting the requirements of the project. To fully design a battery using this lithium ion system, further cell testing was required.

The aim of this further cell testing was to identify the maximum power available from the cell. Similar to motors, cells typically have a constant current/power rating (the current/power that the cell can sustain so that the cell completely drains of energy without over heating) and a peak current/rating rating (the current/power that a cell can sustain for a short period of time). The aim of the testing was to identify the current/power that can be taken from the cells in a race situation.

12 BATTERY SYSTEM TESTING AND DESIGN

12.1 Introduction

An appropriate battery chemistry and cell has been identified for use in a hybrid Westfield Sportscars racing car. The selection of this cell was based on information contained within manufacturers' datasheets. However, the information contained on the datasheets is not sufficient to gain a full understanding of how the cells can be used as part of a hybrid drivetrain.

Cell datasheets quote a maximum constant current that can be discharged from the cell. However, the voltage that the cell will drop to while it is discharging at this current is not given and so an accurate indication of the power of the cell during these conditions is not known. Testing of the chosen cell is required to fully understand the maximum power limits of the cell. Once these power limits are understood, these can be fed back into the simulation tool to understand the effect of different battery configurations. Once this is known, the number of cells required in the battery will be known which can be used to determine the optimum battery configuration.

For the purpose of this project, only maximum constant power will be investigated. Whilst the power of the cell can be increased for short bursts (peak power), this will require management of the cell temperatures by the battery management system and may mean that the driver has varying amounts of power available, dependent on the temperature of the cells. If the system is designed to work using only the maximum constant power of the cell, a constant power should always be available to the driver to maintain a constant feel to the system.

Therefore, the aim of this chapter is to identify an appropriate battery storage system configuration for use in the hybrid Westfield Sportscars racing car. This was achieved by cell testing to understand the constant power capabilities of the chosen lithium ion cell. This information was then used to determine the effect of different battery configurations on 0 to 26.8ms^{-1} (0-60 mph) acceleration times. The scope of this chapter does not include full characterisation of the cell in terms of its internal resistance, polarisation characteristics and activation characteristics as this information is not required to quantify the maximum power of the cell. More information on this can be seen in the literature [22, 106, 107].

12.2 Methodology

12.2.1 Battery Testing

The power capabilities of the lithium ion cell were measured by placing a charged cell onto a load bank. The current draw and voltage of the cell was then recorded whilst the cell was discharged. Twelve tests were carried out, with different resistive loads applied. The load bank values are shown in Table 33.

Test	Load
Test 1	0.3Ω
Test 2	0.15Ω
Test 3	0.1Ω
Test 4	0.075Ω
Test 5	0.06Ω
Test 6	0.05Ω
Test 7	0.0428Ω
Test 8	0.0375Ω
Test 9	0.0333Ω
Test 10	0.03Ω
Test 11	0.0272Ω
Test 12	0.025Ω

Table 33. Cell Test Resistive Loads

Based on the cell manufacturer’s operating recommendations, the test was stopped when the voltage of the cell voltage dropped to 2V. The temperature of the cell was monitored and if the cell reached a temperature of 60°C the test was stopped. The tests were carried out in still air with a controlled ambient temperature of 27°C.

Between the tests, the cells were charged at a constant current rate of 5A. Once the voltage of the cell reached 3.6V, the charging was stopped, with no constant voltage charging period. Whilst not entering a constant voltage phase of charging will result in the cells not being fully charged, it is representative of how the cells could be charged during in-vehicle use if regenerative braking was used.

The average power for each test (P_{avg}) was determined using the average current (I_{avg}) and the average voltage (V_{avg}) seen throughout the duration of the test (T_{test}), as shown in Equation 21.

$$P_{avg} = I_{avg} \times V_{avg}$$

Equation 21

12.2.2 Battery Design

Using the data from the battery testing, a maximum constant power level was determined. Simulations were then carried out to determine the effect of the battery power, measured in the number of cells utilised, on the 0 to 26.8ms^{-1} (0-60mph) acceleration time of the vehicle. The mass of the battery pack was varied depending on the number of cells utilised. An overhead of 50% of the cell mass was used to represent the additional mass of the other parts of the additional components of the battery pack (bus bars, electronics, packaging etc) The parameters for the simulation are shown in Table 34.

Vehicle Parameters	Parameter Value
Base Vehicle Mass (kg)	650
Energy Storage Mass (kg)	Cell Mass + 50%
Gearing Mass (kg)	0
Total Motor Mass (kg)	60
Tyre Rolling Radius (m)	0.280
Final Drive Ratio	3.92
Gear Ratios	[3.61 2.08 1.36 1 0.76]
Engine Torque (Nm)	[20 36 46 54 62 75 87 102 117 126 137 149 160 169 180 190 198 205 217 226 235 243 247 258 264 257 254 145 237 217]
Engine Speeds (rads^{-1})	[152 168 183 199 209 225 240 267 283 303 330 356 377 398 413 434 429 476 497 513 529 550 565 581 591 607 618 638 649 660]

Table 34. Vehicle Parameters for Battery Simulation

12.3 Results

12.3.1 Battery Testing

The results of each of the 12 tests are shown in Table 35. Discharge Test Results

. Test 1 was not left to fully discharge as the equipment used to log the data was unable to display information for longer than 8 minutes. Tests 9, 10, 11 and 12 were stopped early due to the temperature of the cell reaching 60˚C. After Tests 9, 10, 11 and 12, the cell temperature reduced to 50˚C after six minutes at rest. The ambient temperature was set at 27˚C.

Test	**Average Current I_{avg} (A)**	**Average Voltage V_{avg} (V)**	**Test Time T_{test} (s)**	**Average Power P_{avg} (W)**
Test 1	10.6	3.08	440	32.7
Test 2	18.9	2.84	413	54.2
Test 3	27.6	2.77	286	76.6
Test 4	34.4	2.65	222	91.4
Test 5	40.7	2.56	181	105
Test 6	45.5	2.47	165	113
Test 7	52.1	2.45	145	128
Test 8	56.0	2.29	135	129
Test 9	62.8	2.30	63	145
Test 10	65.3	2.23	62	146
Test 11	67.7	2.13	57	145
Test 12	73.5	2.08	56	153

Table 35. Discharge Test Results

It can be seen that the maximum average current draw seen was 73.5A. However, at this current, the cell heated rapidly and the test was stopped before the cell was fully discharged. It can be seen that only 1.15Ah of charge was dissipated before the cell was stopped, compared to an average of 2.12Ah discharged between Test 1 and Test 8.

During Test 8, the cell was able to discharge completely, at an average current of 56A, without reaching the 60°C recommended maximum temperature limit. This corresponds to an average power of 129W. The graphs, showing the change of voltage and current for the duration of each test can be found in Submission 4 of this Engineering Doctorate [7].

12.3.2 Battery Design

The effect of different numbers of cells on vehicle acceleration is shown in Figure 37. It can be seen that as the number of cells used in the battery increases, the 0 to 26.8ms^{-1} (0-60mph) acceleration time tends towards approximately 3.8 seconds. With battery sizes of 400 cells or more there is very small decrease in the 0 to 26.8ms^{-1} (0-60mph) acceleration time.

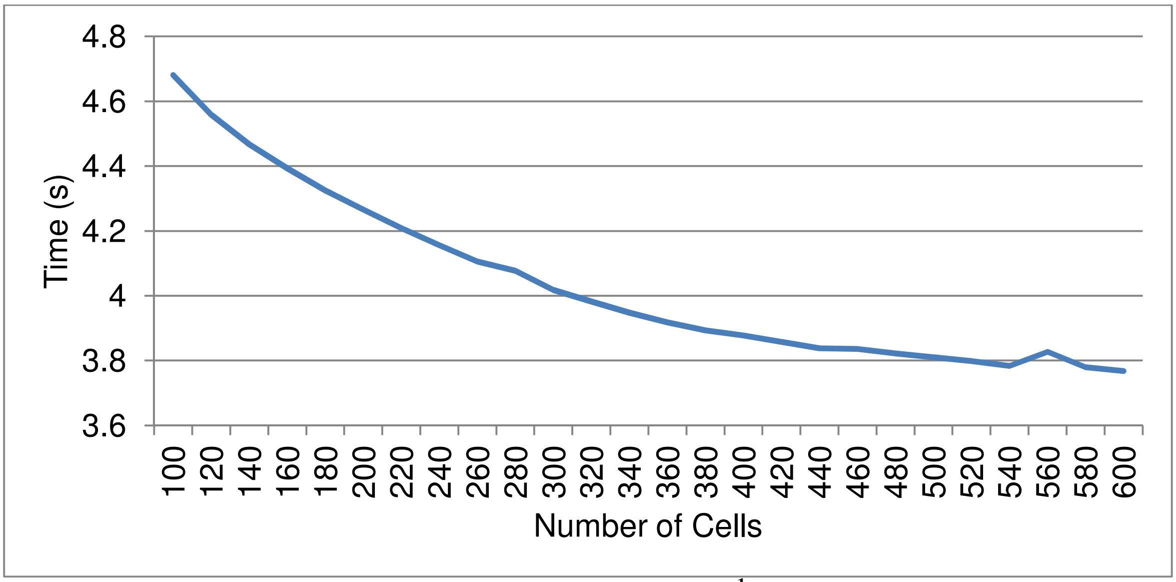


Figure 37. Effect of the Number of Cells Utilised on o to 26.8 ms^{-1} Acceleration Time

12.4 Discussion

It has been shown, in Test 8, that the chosen call can be discharged at an average rate of 129W, without reaching the temperature limit of the cell. Figure 38 shows the current and voltage trace recorded during Test 8. It shows that the cell initially drops (after a few seconds) to a minimum voltage of 2.22V and a minimum current of 54.4A at 71 seconds. This corresponds to a cell power of 121W. At 153 seconds the output has increased to 2.388V and 58.7A, corresponding to a cell power of 169W.

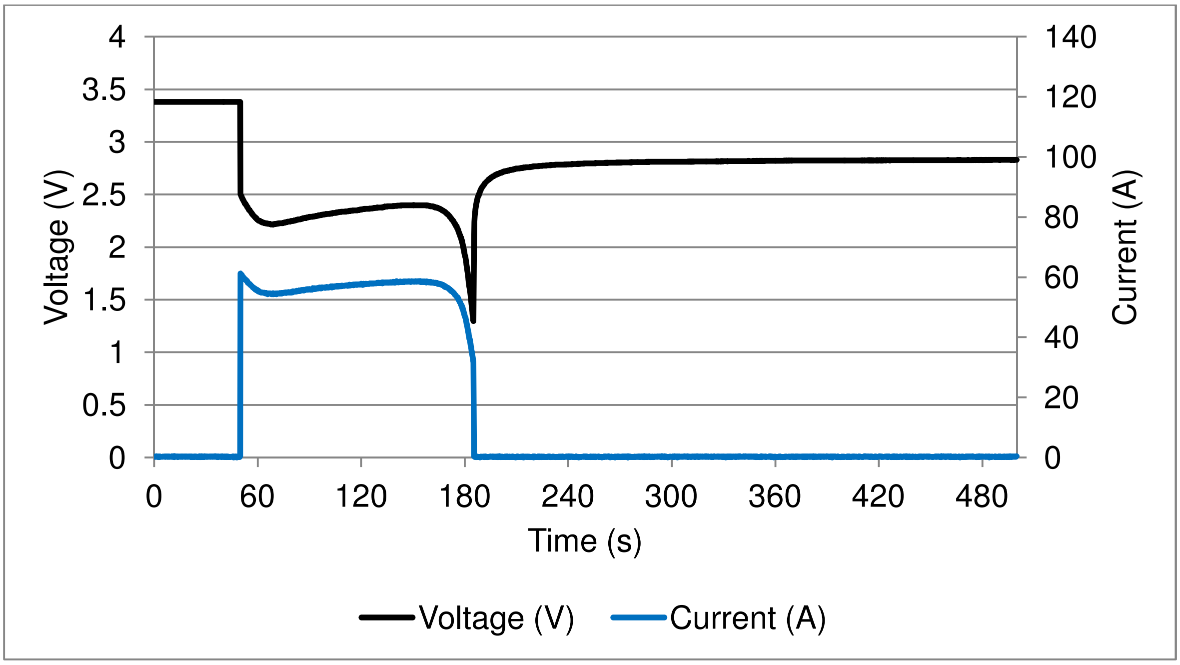


Figure 38. Test 8 – Current and Voltage Results

Part of this change is due to the transient response characteristics of the cell. When the cell first discharges, two capacitor/resistor networks are discharged, resulting in the curved voltage response seen at the start of discharge [22, 106, 107]. The effects of these two capacitor/resistor networks are known as polarisation and activation. The voltage drop that the cell sees is due to the internal resistance of the cell. On the higher current discharges, such as Test 8, the voltage of the battery is seen to increase after it has finished polarisation and activation. This is due to the temperature of the battery increasing, which reduces the internal resistance of the cell, allowing energy to discharge at a higher rate.

With the right temperature management, it may be possible to increase the output of the cell. However, to achieve this, the cell would need to be run at, or near, its maximum recommended operating temperature (60°C). The problem with this is that the thermal inertia of the cell is such that it took six minutes for the cell to cool down to 50°C. Therefore, the only way this could be achieved is through an active cooling system of the cells. Whilst this may allow a higher power from the cells, the cost and mass of an active cooling system may be too high for this project..

Limiting the maximum power to 129W per cell allows the system to ensure that it can run at a constant power, meaning the power of the system does not change for the driver during use. It also means that the pack should never be able to reach a dangerously high temperature. However, depending on the installation of the battery and its cooling efficiency, it may be possible to raise this power limit following testing.

Using a power limit of 129W per cell it has been shown that, using a battery comprising of the tested cells, the 0-60 mph acceleration time tends towards approximately 3.8 seconds. With a 400 cell battery, the 0 to 26.8ms^{-1} (0-60mph) acceleration time is 3.89 seconds. The average acceleration time of a battery with between 400 and 600 cells is 3.81 seconds. Therefore there is little advantage in having a battery system with more than 400 cells as, whilst there may be a small decrease in 0 to 26.8ms^{-1} (0-60mph) acceleration time, there will be an increase in the cost and mass of the system.

The datasheet for the cell suggested that the maximum constant current for the cell was 70A, with no indication of the voltage at this point, making it difficult to calculate cell constant power. Through experimentation, it has been shown that the average maximum constant cell current is 56A, with an average power of 129W. Whilst this is lower than the power used to determine the cell suitability for the project, through simulation, it has been shown that, even with this lower power, a 0 to 26.8ms^{-1} (0-60mph) acceleration time is possible with a 400 cell system (51.6kW). There may also be scope to increase this power, depending on the battery installation and cooling characteristics, with in vehicle experimentation.

In addition, using the cells at their maximum constant power is closer to what could be achieved if the technology were to transfer to the road. Many hybrid electric vehicles currently in motorsport, such as Formula One, use the cell peak power. Whilst this allows extra power to be available, it results in the life of the battery being restricted to a single race, making the transfer of technology to the road too expensive. Using the cells near their maximum operating limits also introduces reliability issues, further increasing cost.

The characteristics of this battery, high discharge power and low charging power, dictate the control strategy for this system. As the amount of energy able to be recovered from the brakes is low, due to the limited braking time during a race, the majority of energy will have to be provided by charging the system from the mains electricity supply. There will then be a restricted amount of energy available to the driver for the race. A system operating in this way would be new to motorsport and, if successfully implemented, would be considered innovative.

12.5 Conclusions

Through a process of architecture simulation, motor simulation, energy storage comparisons, testing and further simulation, a design for a hybrid drivetrain has been presented that can be integrated into a prototype hybrid electric Westfield Sportscars racing car.. This drivetrain, arranged in a through-the-road parallel hybrid architecture, consists of an Oxford YASA Motors dual motor system powered by a 51.6kW battery pack. The exact design of the battery pack will be dependent on the packaging available and the system voltage requirements. This is discussed in Chapter 13.

Unlike hybrid electric drivetrain design for other forms of motorsport, the sole design aim has been to increase the performance of the vehicle, without consideration of the system operation (predetermined by the technical regulations of other race series) being taken into account. The result of this is an innovative drivetrain that can accelerate a Westfield Sportscars Sport Turbo from 0 to $26.8ms^{-1}$ (0-60mph) in less than four seconds with a unique control strategy. Whilst the system can utilise a boost function, similar to Formula One, it does not require energy recovery from the brakes. The result of this is a unique control strategy where the driver is given a set amount of electrical energy and would need to choose how and when they use that energy throughout the entire race. This innovative approach to energy management would be a new concept to motorsport. The next step in the process is to investigate the feasibility of integrating this system into a Westfield Sportscars Sport Turbo.

12.5.1 Future Work

The testing that has been carried out was sufficient to prove the maximum sustained discharge current for the battery cell. This has provided a safe level of power capability, particularly if the user is able to use the entire energy storage in one event. Further testing to characterise the cell would be beneficial to further understand of this power level could be increased, but limited to many discrete acceleration events.

This testing could take the form of simulating various durations of pulses, simulated to occur over a race representative drive cycle. The magnitude and length of the pulses could then be varied to investigate the effect of increasing the maximum power limit from the batteries. Another approach would be to characterise the cell, in terms of its internal resistance and build up a simulation model of the cell. This model could then be used to perform many simulations of different pulse magnitudes and lengths. For both of these testing approaches, information on the cooling rate of the cells in the designed battery is required once the battery pack has been fully designed and integrated into the vehicle.

13 VEHICLE INTEGRATION

13.1 Introduction

An innovative hybrid electric vehicle drivetrain, suitable for use in a Westfield Sportscars Sport Turbo racing car, has been specified through investigations into the project and customer requirements, simulation and experimentation. To prove the technical feasibility of this drivetrain, it was necessary to implement this drivetrain into a Westfield Sportscars Sport Turbo chassis. The main systems that required integration were:

- Chassis and Suspension
- Motor and Inverter
- Battery
- Electric Distribution System
- Control System

Design of the system was carried out with Autodesk Inventor 2008, a Computer Aided Design (CAD) system, using data on the Sport Turbo chassis from Westfield Sportscars as a starting point.

The aim of this chapter is to show the feasibility of installing the drivetrain, the components for which have been identified in previous chapters, in a Westfield Sportscars Sport Turbo chassis. The scope of this chapter does not include the suitability of manufacturing techniques or part availability for the small series production of the system. However, manufacturing techniques that are available to Westfield Sportscars and off the shelf parts were used wherever possible.

This chapter documents only the major modifications that were required to the Westfield Sport Turbo Chassis. The total mass of the hybrid system was found to be 126kg, with the total mass of the vehicle, once built, found to be 742kg. A breakdown of the hybrid system mass, as well as a detailed list of all the modifications required to the standard vehicle, including engineering drawings, can be found in Submission 5 of this Engineering Doctorate [8].

13.2 Chassis and Suspension Integration

To enable the car to drive the front wheels, modifications were required to be made to the front suspension system, as well as to the front uprights. The front suspension was modified so that spring and damper unit was mounted inboard, on the front upper chassis rail. The coilover spring/damper unit was then actuated by a push rod. As the push rod was a smaller diameter than the coilover spring/damper unit, this allowed driveshaft access to the wheels. Figure 39 shows the driveshaft (shown in red) clashing with the coilover spring/damper unit (shown in yellow). The modified assembly, with inboard coilover spring/damper unit is shown in Figure 40. Figure 40 also shows the modifications made to the steering rack position to accept the electric motors in the front of the chassis.

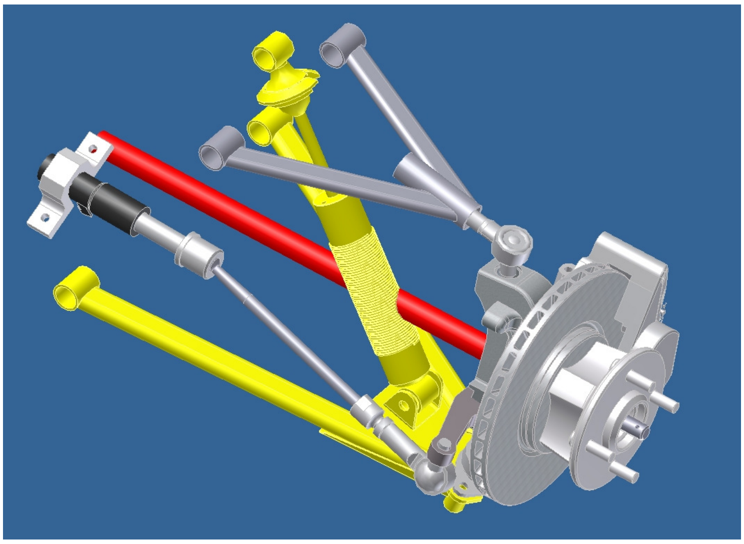


Figure 39. Sport Turbo Standard Front Suspension and Axle Line

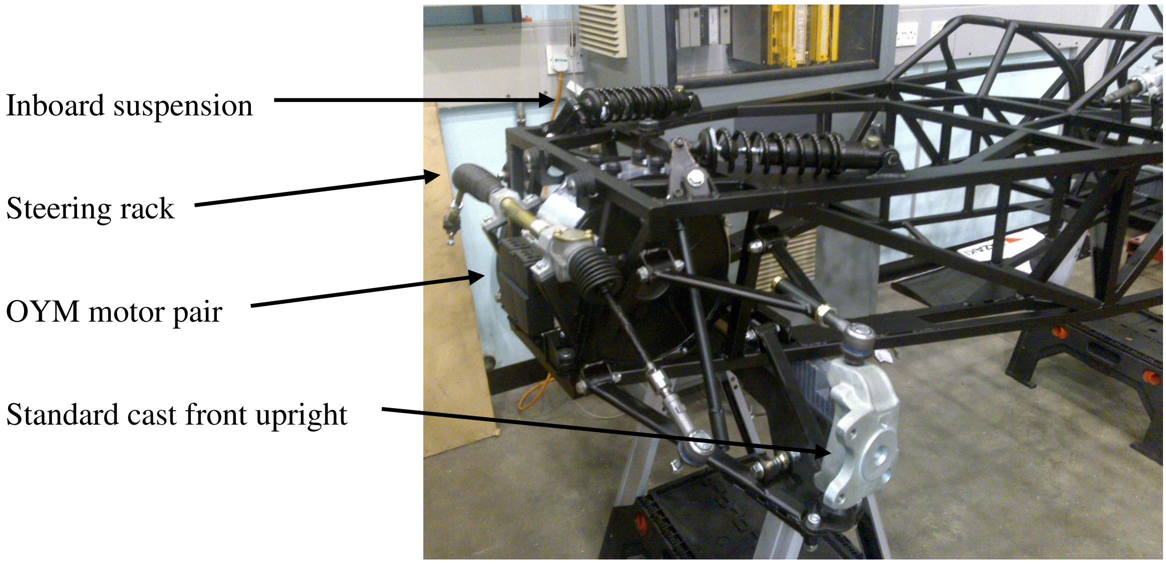


Figure 40. Inboard Suspension and Modified Steering Rack Position

To accept drive from the driveshaft, the front uprights were modified. This was achieved by replacing the standard cast uprights, shown in Figure 40 with fabricated alternatives. These alternatives used the standard rear upright wheel bearings and utilised off the shelf constant velocity joints. This is in line with Westfield Sportscars' policy of using off the shelf components, such as bearings and constant velocity joints, where possible. A driven front upright is shown in Figure 41.

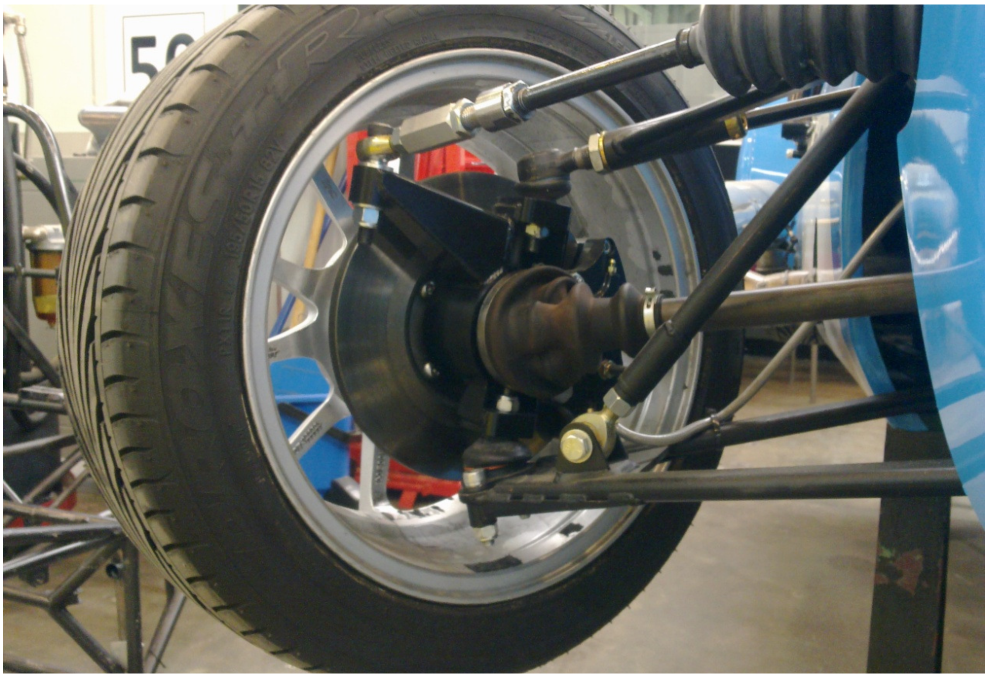


Figure 41. Driven Front Upright

With the vehicle now having drive to the front wheels, it is possible for 'torque steer' to occur when a boost is requested by the driver. Torque steer occurs when the driver feels the car pull strongly to one side, as a result of change in engine torque, particularly during periods of high acceleration [108]. To retain driver control of the vehicle, the torque steer effect should be minimised. The root causes for Torque Steer are:

- Asymmetric driveshaft angles, e.g. due to
    - Asymmetric design of the vehicle, e.g. different driveshaft length
    - Transient movement of the engine
    - Tolerances in engine mounts
- Different driveshaft torques left to right
- Suspension geometry tolerances
- Unequal traction forces due to road surface (μ-Split)

Therefore, to reduce torque steer occurring in the drivetrain, the driveshafts were kept to the same length with the motor pair being mounted symmetrically and lateral movement of the motor was restricted by the design of the motor anti-vibration mounts. The torque requests from the motors were set to the same value so that the driveshaft torque left to right was equal and the suspension was set up by Westfield Sportscars to reduce any tolerance in suspension geometry. Unequal forces due to road surfaces are dependent on the track being raced on.

However, one advantage of having two motors driving the front wheel is that there is independent motor control, allowing for torque vectoring. Torque vectoring utilises the effect of torque steer to improve the cornering ability of a vehicle by purposefully requesting more torque from one motor than the other [109]. Whilst the drivetrain has the potential to have torque vectoring implemented, it was not necessary for the initial stage of the project, had been found not as popular as the boost function in the customer survey and was therefore not investigated or implemented.

13.3 Motor and Inverter Integration

The Oxford YASA Motor (OYM) dual motor system utilises two motors mounted back to back rotating at wheel speed (without the need for reduction gears). Therefore, to drive the front wheels, the OYM motor pair needed to be mounted in the front of the chassis, in line with the front axle line. Through relocation of the steering rack, forward of the front chassis members, the OYM motor pair was successfully mounted in the front of the chassis on anti vibration mounts. This is also shown in Figure 40.

The inverters, which convert the DC voltage of the battery to the AC voltage used by the motors, were mounted in the passenger foot well area of the vehicle. Whilst this was not an ideal position, as passenger space was restricted, this was accepted as suitable for the prototype vehicle as a race car would not normally have a passenger seat. The position of the inverters, along with the electrical distribution box, is shown in Figure 42.

Figure 42. Inverters Mounted in Passenger Foot Well

13.4 Battery Integration

With the cell that was chosen for the battery system, it would have been possible to create different configurations of battery system. The number of cells determines the power that is available, however, these cells can be placed either in combinations of series and parallel to vary the battery voltage. For example, it was determined that approximately 400 cells were required. With 400 cells in series, each with a nominal voltage of 3.3V, this would have resulted in a 1320V battery system. With 2 in parallel and 200 in series, the battery would have had a nominal voltage of 660V. With 4 in parallel and 100 in series, the battery system would have had a nominal voltage of 330V.

For the final design, a battery configuration of 132 series elements, each element consisting of three cells in parallel was used, giving a nominal voltage of 435.6V. A nominal voltage of 435.6V was chosen because the discharged voltage of the pack was approximately 375V and, at this voltage, the base speed of the motors was higher than the maximum velocity of the vehicle. This was important because field weakening of the motors was not implemented in the inverter software (allowing the motors to be controlled above their base speed). Without field weakening control, above base speed the counter-electromotive force of the motors is greater than the battery voltage and will attempt to charge the battery. Therefore, keeping the base speed of the motor above the maximum velocity of the vehicle prevents uncontrolled charging of the battery.

The battery was split into two battery packs, each mounted under the seats of the car, protruding beneath the bottom chassis rail by 50mm. Each of the two battery packs were split into 11 modules. Each module had a nominal voltage of 19.8A. The pack was designed so that, when assembled, it was not possible to access a voltage higher than 19.8V, protecting the person assembling the pack from electric shock (voltages below 60V are considered safe [81]). The specification of the system, packs and modules are shown in Table 36 How the packs and modules were constructed is shown in Figure 43 and Figure 44.

Specification	Battery System	Pack	Module
Parallel Cells	3	3	3
Series Strings	132	66	6
Cells	396	198	18
Nominal Voltage (V)	435.6	217.8	19.8
Maximum Voltage (V)	475.2	237.6	21.6
Minimum Voltage (V)	264	132	12
Charge (C / Ah)	8280 / 6.9	8280 / 6.9	8280 / 6.9
Capacity (MJ / Wh)	11 / 3000	5.4 / 1500	0.49 / 137
Maximum Constant Current (A)	180	180	180
Maximum Constant Power (kW)	51.48	25.74	2.34

Table 36. Battery System, Pack and Module Specifications

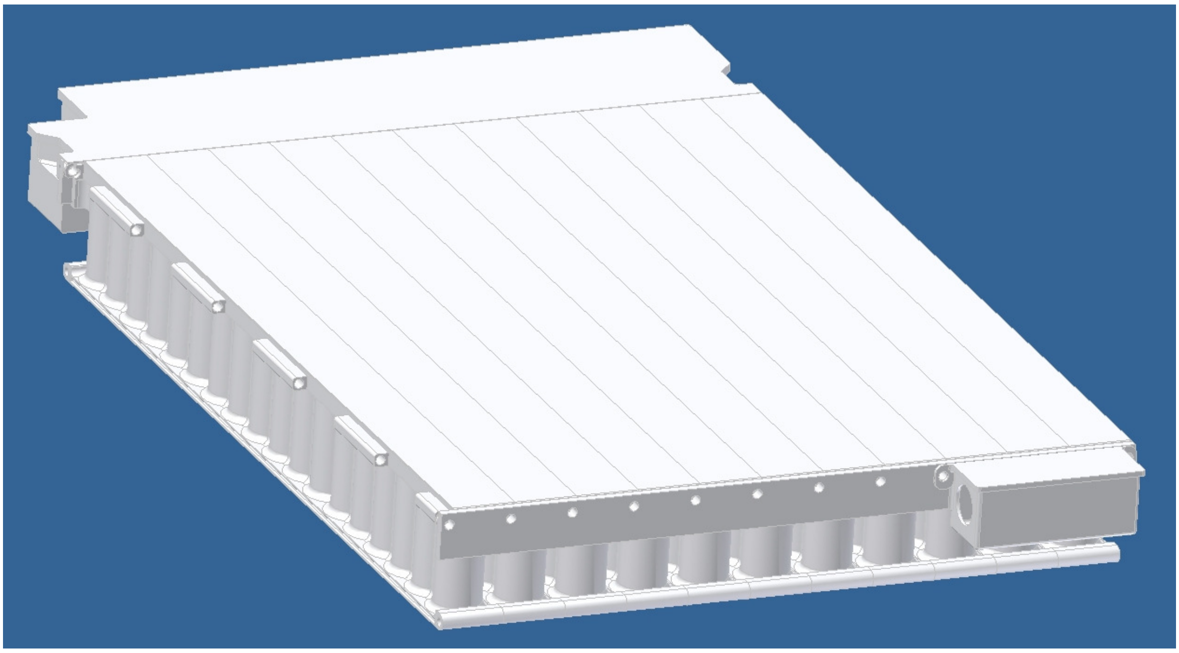


Figure 43. Battery Pack

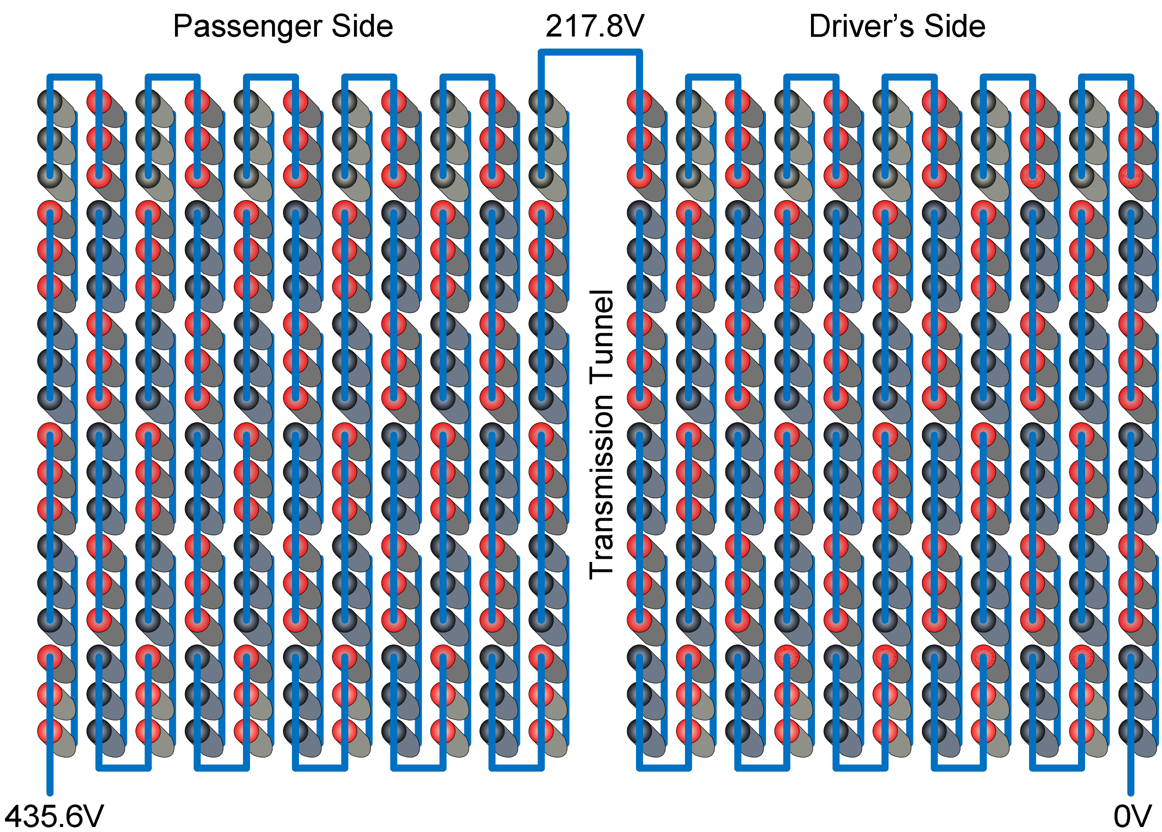


Figure 44. Battery System

The casing for each module was made from rapid prototyped PA2200 (Nylon 12). This process allowed the packaging to be shaped to enable air flow between the cells, allowing for extra cooling while the vehicle is moving. Figure 45 shows one of the battery packs mounted beneath the vehicle.


Figure 45. View of a Battery Pack underneath the Vehicle

A battery monitoring system was developed that was capable of monitoring the voltage of each cell and the temperature at 8 different points. This was controlled by a CompactRIO data acquisition system from National Instruments. This data acquisition system was integrated with the electrical distribution system to control driver inputs, the battery contactors and provide communications with the inverters over Controller Area Network (CAN).

13.5 Electrical Distribution System Integration

A low voltage electrical distribution system (EDS) was developed that was almost completely separate to the standard electrical system on the car. This enabled the system to be an add-on part to the standard EDS (for retrofitting) whilst also protecting the operation of the vehicle in the event of a fault with the hybrid system. However, it was necessary to the link the throttle position, clutch pedal and brake pedal sensors between the two systems. Power was provided to the EDS through the onboard vehicle 12V starter battery.

The hybrid system was activated through the use of an E-Stop button mounted on the dashboard of the vehicle. The E-Stop (along with the ignition signal from the key) provided power to the inverters and to the National Instruments CompactRIO system, which, when activated pre-charged the inverters and put the system into a ready state. Two paddles, mounted behind the steering wheel then allowed the driver to initiate the boost. This can be seen in Figure 46. More information, including wiring diagrams and component specifications can be found in Submission 5 of this Engineering Doctorate [8]

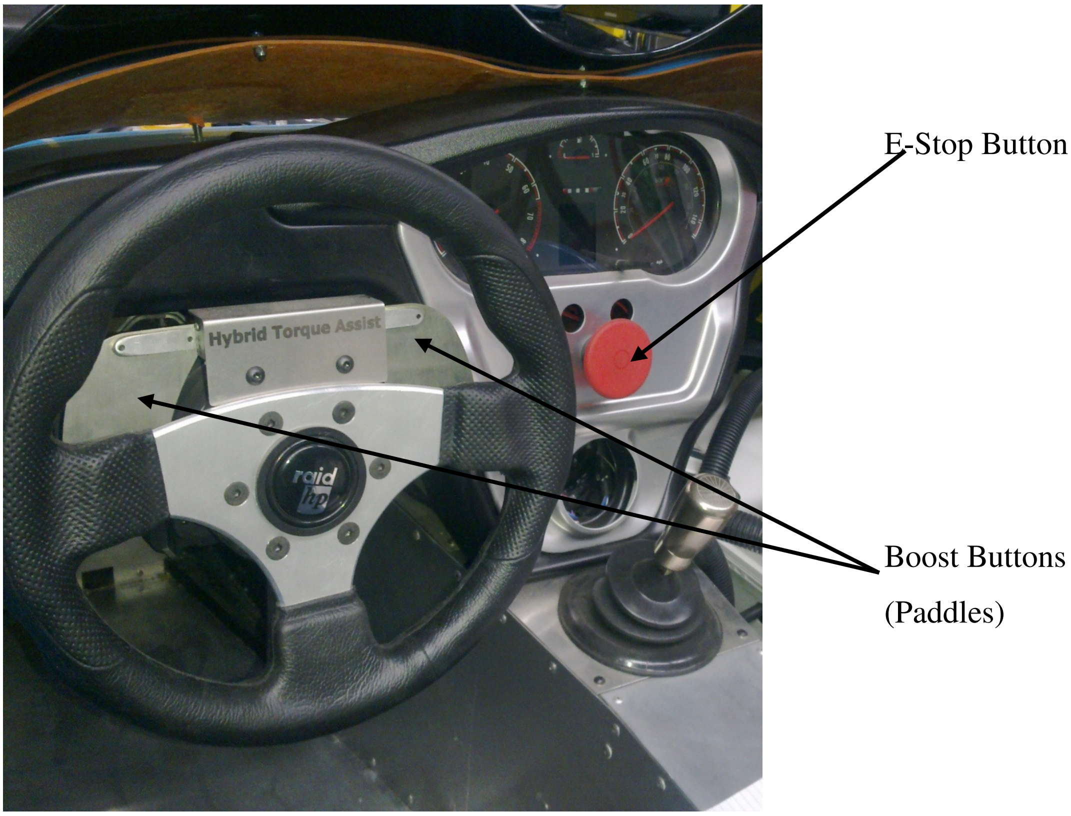


Figure 46. Boost Buttons (Paddles) and E-Stop Installed in Prototype Vehicle

13.6 Control System Integration

The hybrid drivetrain required a control system to allow the safe control of the motor and the battery system. However the requirements of the control system for use in a club motorsport vehicle were different to that of a typical HEV.

The control system for most HEVs is optimised to automatically control the charging and discharging of the energy storage device. For a road vehicle, this is usually optimised for gains in fuel economy and can involve an element of ensuring that the system can sustain charge over a given drive cycle (so that there is always some energy available) [16]. However, the requirements for club motorsport are not for fuel economy and it could be argued that having charge left at the end of a race is wasteful (as this could have been used to improve race performance) and therefore a typical HEV control system is not suitable for use in a hybrid electric club motorsport race car.

One of the requirements for the drivetrain is that the driver remains in control of the vehicle at all times (taken from Table 11). Therefore, any control system should be as unobtrusive as possible and should concentrate on maintaining the safety of the system and not allowing the driver to put the system into an unsafe state. However, some aspect of control is required. For example, the decision of when the drive through gear changes should come from the driver and not the control system, but the control system will have to be designed to allow the driver to drive the electric motors through the gear changes.

Furthermore, there is the possibility that a poorly designed control system could have a detrimental impact on the braking and handling of the vehicle. While reduced handling performance is not desirable, an impact on the braking system could be dangerous. Therefore, the introduction of regenerative braking needs to analysed in more detail.

13.6.1 Regenerative Braking

A hybrid drivetrain has been developed that uses a through the road hybrid architecture, with the front wheels powered by electric motors and the rear wheel powered by an internal combustion engine. If required, significant braking effort could be achieved through the motors on the front wheels regenerating energy back into the energy storage device. If this approach is taken, then the braking needs to be smooth, safe. For motorsport use the braking also needs to be consistent as drivers use markers on the track to dictate the points at which braking should occur. If braking force is not consistent, then the system of using markers to brake cannot be used and could be dangerous. Therefore, there cannot be any difference in the braking efficiency at different times, for example when the energy storage device is full or empty.

To achieve a safe and consistent regenerative braking system is possible, but could be expensive and difficult to implement. To determine whether such a system is required, an analysis of how regenerative braking can could be used on a track was undertaken, using the Silverstone National Circuit as a basis. Figure 47 shows a velocity trace of 1 lap of the Silverstone National Circuit in a Westfield Sportscars racing car.

The battery system installed in the car has 396 cells, enough to produce 51.5kW and an energy content of 11MJ. If an acceleration event lasts 4 seconds at 51.5kW, 206kJ of energy will be consumed, enough for approximately 50 acceleration events. If this is split evenly over 20 laps, then the driver could do 2.5 acceleration events per lap, using 515kJ per lap over 10 seconds.

During the battery system testing it was found that each cell could be charged at up to 10A per cell. However, at above 5A, the temperature of the cell began to rise significantly, reducing the effective charging current to 5A. It was observed that when charging at 5A, a cell would move from a nominal voltage of 3.3V to 3.45V. From Equation 1 it can therefore be found that the power accepted by the battery is 17.25W, with 0.75W of this power lost as heat. Therefore, with 396 cells, the maximum constant charging power of the battery system is 6.83kW, including 297W lost as heat.

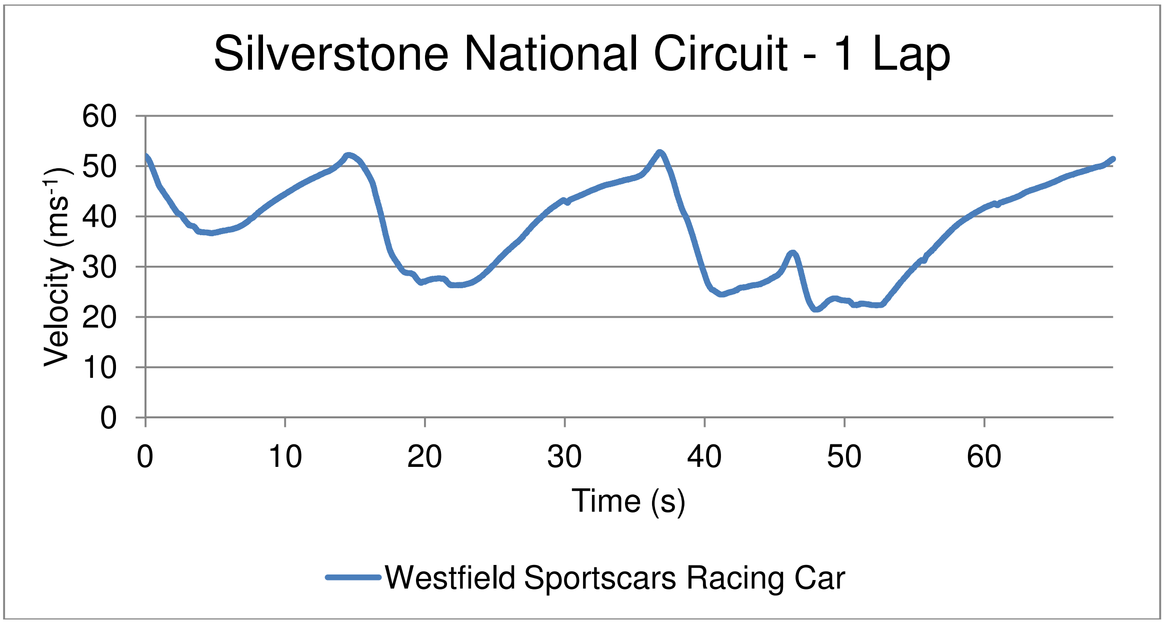


Figure 47. Silverstone National Circuit

The lap shown in Figure 47 lasts for 69.2 seconds, 55.6 seconds were spent accelerating and 13.6 seconds were spent decelerating. If the batteries were charged at their maximum for 13.6 seconds, the braking energy that could be converted to electrical energy would be 92.9kJ. Due to 4.04kJ being lost to heat, the energy recovered back to the batteries would be approximately 88.8kJ.

At an approximate discharge rate of 515kJ per lap and a maximum charge rate of 88.8kJ per lap, it would not be possible to have a system by where the energy used per lap could be recuperated through regenerative braking on the same lap (in a similar way to Formula One). Furthermore, the amount of energy recovered is small enough that it is unlikely to have a large effect of the viability of the system and is not a barrier to the initial implementation of the system. Therefore, the decision was made that for the initial hybrid drivetrain that regenerative braking would not be utilised.

13.6.2 Motor Control

The control system for the hybrid electric drivetrain was implemented in National Instruments LabVIEW and run on the National Instruments CompactRIO data acquisition system present on the car. The control system was responsible for:

- Monitoring the battery voltages and cells
  - Restricting power if a cell voltage or temperature goes out of range
- Management of the battery pack contactors, including pre-charge control
- CAN communication with the inverters
- Controlling the relays powering the inverters
- Interpreting the throttle, brake, clutch and boost button signals
- Ensuring safe system operation.

There were two main control loops within the control system. Figure 48 shows a state flow diagram of the main control loop that was implemented within the CompactRIO FPGA. The primary aim of this control loop is to manage the contactor protecting the battery. If at any point the internal variable 'Enable_Motors' is false, then the system will shut down the inverters and open the contactors. Within this system, there is the 'Set Torque Demand' subsystem that controls the torque demand sent to the motors. The details of this subsystem are shown in Figure 49.

The 'Set Torque Demand' subsystem controls the torque demands sent to the two motors. The torque demand sent to the motors will depend on the throttle position, brake position, clutch position and the boost button position. It is also designed to allow the driver to drive through gear changes, which is required to meet the expected 0 to 26.8ms^{-1} (0-60mph) acceleration times.

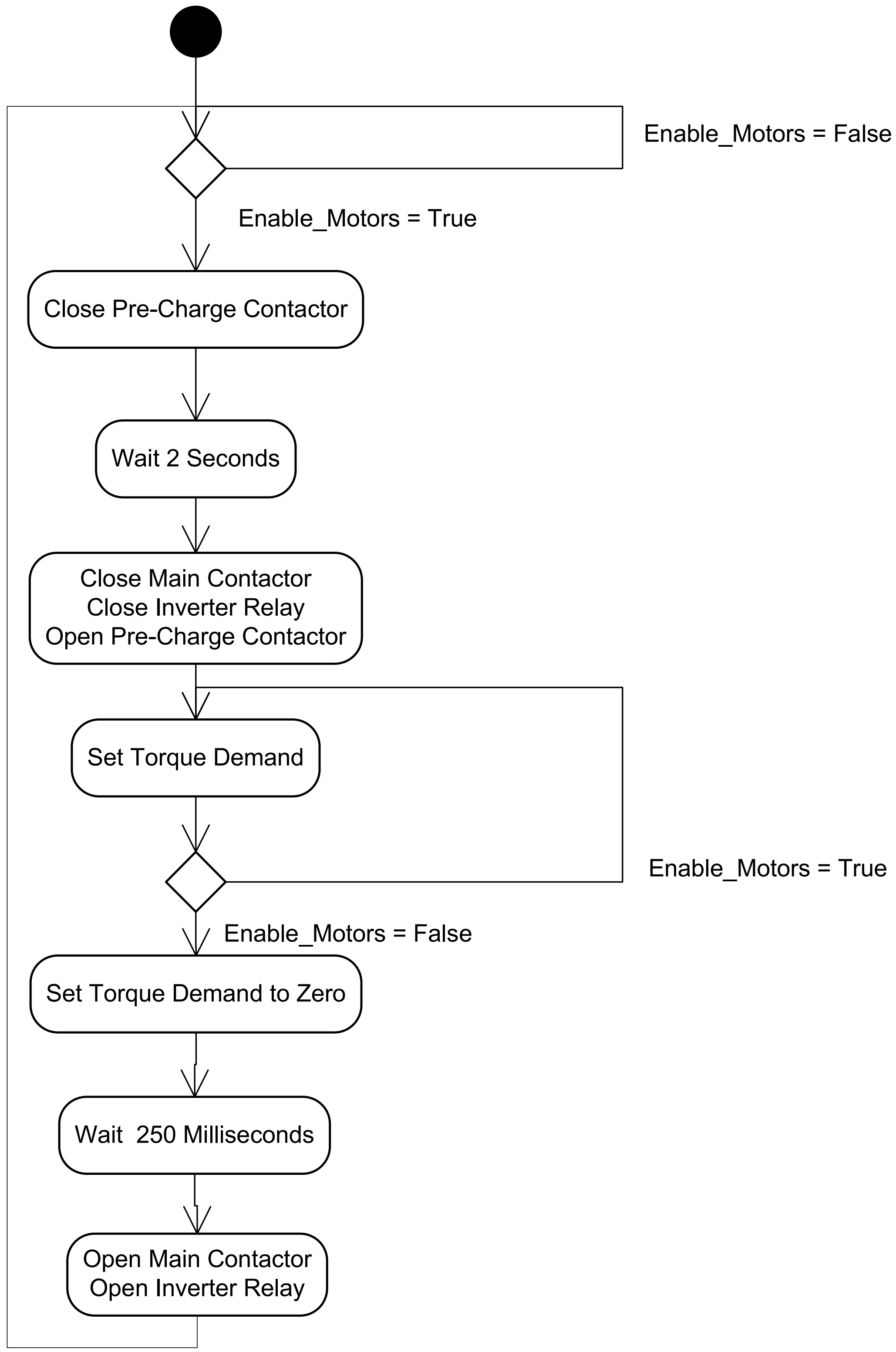


Figure 48. FPGA State Flow Diagram

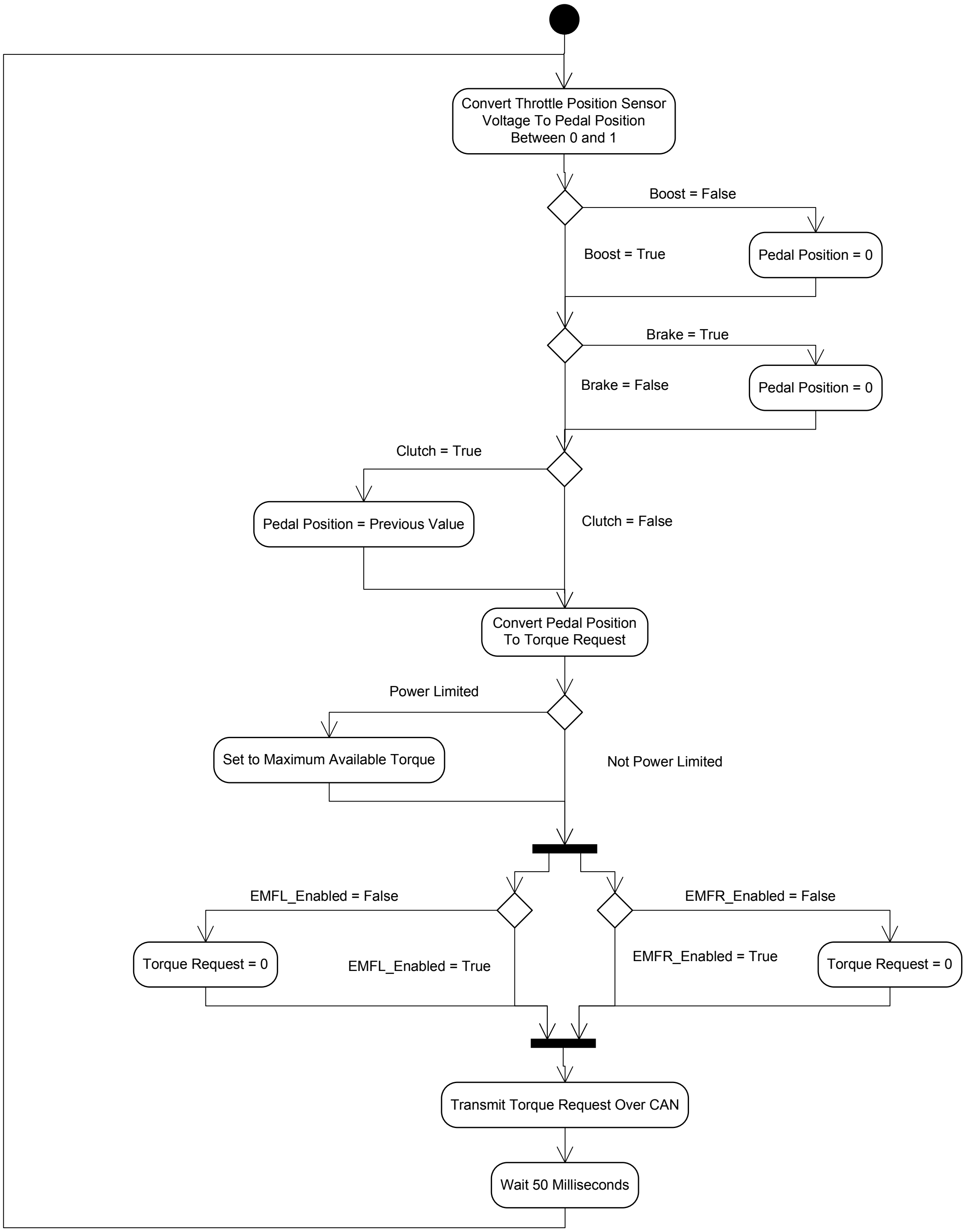


Figure 49. Set Torque Demand Algorithm State Flow Diagram

Once the hybrid system was activated, the control system sent constant torque requests to the motors. If a boost was not requested by the driver, zero torque requests were sent. If a boost was requested, the magnitude of the torque request was proportional to the throttle pedal position. A boost was allowed when the driver pushed one of the boost buttons and the brake pedal was not being activated.

If during a boost event the clutch pedal was activated, then the torque request to the motors was latched (kept to the level prior to the clutch being pressed) until the clutch pedal was released. This was the same system used in the driver model for all of the vehicle simulations, allowing and allowed the driver to use the electric motors to drive through gear changes.

An example sequence for driving through the gear changes is shown in Figure 50 where the following actions can be observed.

1. Time = 0.0s – Driver torque demand at 100% (engine torque request)
2. Time = 0.5s – Driver presses Boost Button, motor torque increases to 100% to match driver torque demand (100%)
3. Time = 1.0s – Driver depresses the clutch pedal to start changing gear, motor torque request is latched to 100%
4. Time = 1.2s – Driver torque demand is reduced to 0% to allow gear changes. Motor torque request stays at 100%
5. Time = 1.4s – Gear changes from 1^{st} to 2^{nd}
6. Time = 1.8s – Driver Torque demand increased to 100% and clutch pedal released. Motor Torque demand follows Driver torque demand again.

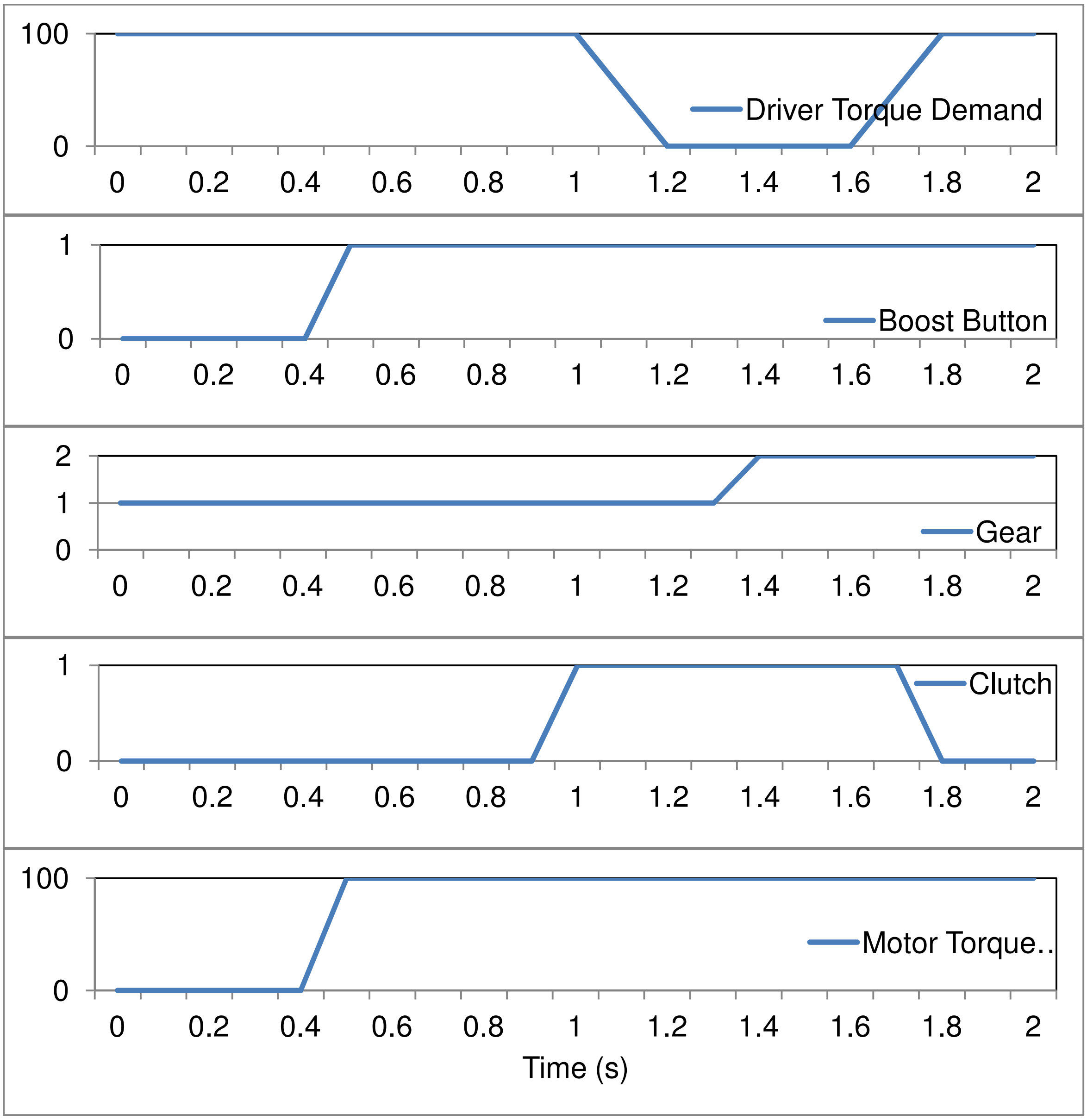


Figure 50. Control System Sequence Diagram for Driving Through Gear Change

13.7 Testing

13.7.1 No-Load Testing

Once the prototype vehicle had been built, testing of the system commenced. Initial tests were performed with no load on the electric motors by having the vehicle raised off the ground. These tests confirmed that the functionality of the system, including:

- Battery contactor control
- E-Stop activation
- Graphical display operation

- CAN communication
- Sensor reading (throttle, brake, clutch and boost)
- System activation (pre-charge control)
- System operation

The system operation was confirmed, with the vehicle raised off the ground, by testing the control of the motors with the accelerator pedal. With the boost button pressed, it was possible to rotate the front wheels of the vehicle with the motors. The brake pedal was shown to interrupt the torque request to the motors and the clutch pedal was seen to correctly latch the motor torque request. However, it was not possible to fully test the torque control of the motors because there was no load on the motors with the vehicle raised off the ground.

13.7.2 On Load Testing

To test the control of the electric motors, the hybrid system was operated with load applied to the wheels, achieved by placing the car on the ground. The internal combustion engine on the car was not started and the gearbox was left in neutral. This allowed the hybrid system to be tested in isolation.

By applying a small torque request to the electric motors, it was found that, whilst the left hand motor operated correctly, the right hand motor attempted to deliver maximum torque, resulting in the motor breaking traction and spinning. Correct operation and control of the left hand motor was proven by disabling the right hand motor. This resulted in the left hand motor being able to drive the vehicle (using only the front left wheel). This is shown in Figure 51, which shows the right hand motor rotational velocity is initially much larger than that of the left hand motor. At 20 seconds the right hand motor was disabled and it can be seen that the motor speeds remained the same and in control. This indicates that, the vehicle controller was correctly requesting torque from the motors, but there was an issue with the right hand motor or inverter.

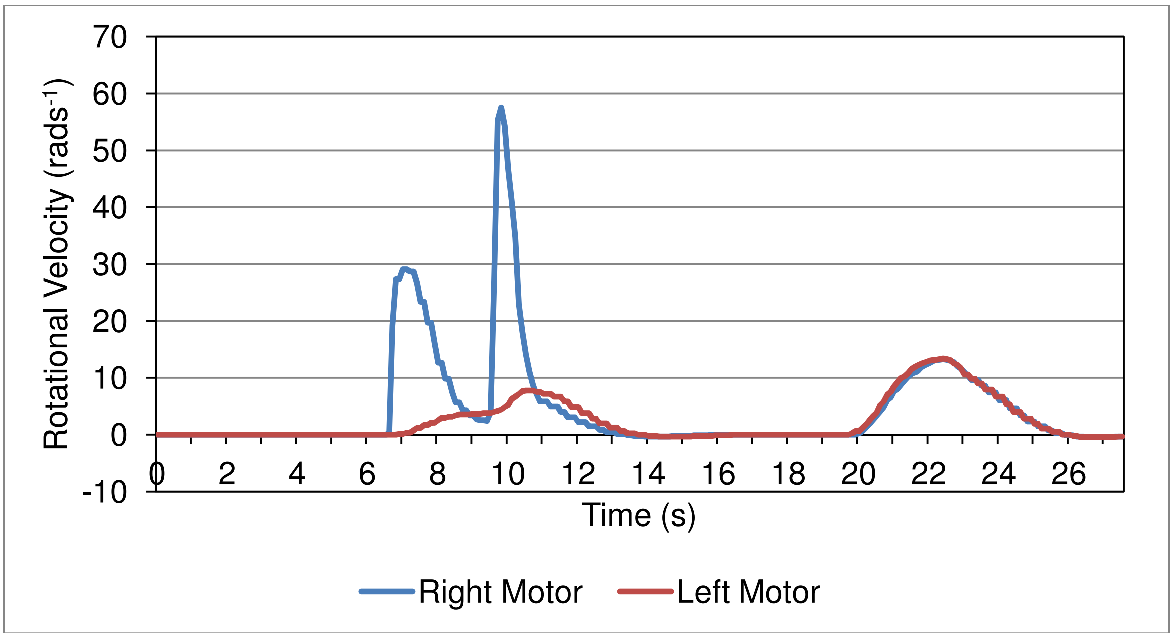


Figure 51. Electric Motor Tests

The test was repeated with an amended control strategy, where the torque request sent to the right hand motor was scaled by 0.1, meaning the maximum torque request that the right hand motor could see was 50Nm. However the results remained the same with the right hand wheel uncontrollable. This would suggest an issue with the motor or with the inverter. It was therefore decided that it was not possible to continue with testing until the issue had been resolved. There were also a number of other issues identified that prevented further testing.

The low speed control of the motors, implemented within the inverters, was unstable. With zero torque request, there was a small 'creep' torque from the motors, with the magnitude of the torque being dependent on the exact rotational position of the motor. The worst case scenario for this occurred when there was a positive 'creep' torque on one wheel and not the other, which resulted in the motors forcing the steering to turn to full lock. As this had an effect on the steering, it was decided, again, that further testing could not continue until this safety issue was resolved.

13.8 Discussion

The work carried out on vehicle integration has shown that it is possible to integrate a hybrid drivetrain into a Westfield Sportscars racing car. Some modification to the existing chassis was required, including raising the height of the seats, modifying the suspension and accommodating the mounting of the motors in the front nose of the car. These changes were not extensive, but were significant and in their current form would preclude the system from being retro-fitted. However, with additional engineering design, it may be possible to design the system to be retrofitted. This could be achieved through the design of conversion kits that did not involve the need to cut or weld parts of the chassis.

The vehicle integration and has allowed for an innovative control system to be developed that is able to meet the unique requirements of this application and club motorsport. The control system does not utilise regenerative braking. By doing this, cost and complexity can be reduced and the impact on the system is minimal as it has been shown that the potential energy that could be recovered in a racing situation is minimal. A boost event is initiated and controlled by the driver, with minimal control being used to add the ability to drive through gear changes. This innovative approach allows the driver to remain in control and retain the thrill of racing, an important attribute for a system designed for club motorsport where the drivers of the vehicles are also the owners.

The strategy to not include regenerative braking also allows the system to have a unique operating principle where the driver is given a set amount of energy for a race and it is up to the driver to manage where they use that energy. This innovative principle could add an additional layer of strategy for the driver, further increasing enjoyment.

Both of the issues identified during testing, an uncontrollable right hand motor and the creep torque, can be attributed to the inverters. While the inverter hardware was a standard part, designed for automotive use, the software within the inverters had been developed by Oxford YASA Motors as a development project. The engineer responsible for the software left the company before it could be finished and tested and, as a result of this, Oxford YASA motors removed support for the inverters, suggesting the use of an alternative third party inverter instead. Unfortunately, this recommendation came after the completion of the project.

By changing the drive system on the car to use different inverters, both of the issues could have been resolved. It has been shown that while it is possible to package the inverters in the vehicle, they would not be electrically compatible with the system. The maximum voltage of the battery in the vehicle was 475.2V, while the maximum voltage allowable by the suggested and supported replacement inverters was 400V. It would also be necessary to replace the position sensors on the motors to work with the suggested replacement inverters.

As well as the cost of the replacement inverters, there would have been significant cost in redesigning and building a replacement battery, involving new cells and new rapid prototyped casings. With appropriate inverters and a redesigned battery system, it has been shown through simulation that the vehicle would be able to achieve a 0 to 26.8ms^{-1} (0-60mph) of below 4 seconds. However, there was not enough budget remaining to allow these modifications and ultimate testing of the system, proving the 0 to 26.8ms^{-1} (0-60mph) time, was not possible. Despite this, the vehicle integration of the system has proved the hybrid drivetrain concept works within a Westfield Sportscars Sport Turbo chassis.

Also implemented, was an innovative control system that allowed the driver to power through the gear changes. This system, which was originally used in the vehicle simulation tool, gave a boost when the driver requested it, but latched the boost request while a gear change was being made, allowing the hybrid drivetrain to drive through the gear changes, reducing 0 to 26.8ms^{-1} (0-60mph) acceleration time. This innovative control system is a significant contributor to the overall reduction in 0 to 26.8ms^{-1} (0-60mph) acceleration time.

13.9 Conclusions

This chapter has shown that the drivetrain that has been developed in previous chapters is able to be integrated into a Westfield Sportscars Sport Turbo. The only components that were not fully integrated were the inverters. These inverters were prototype parts and, due to Oxford YASA Motors no longer recommending the use of the inverters, have been superseded with alternatives. These alternatives are more favourable in terms of size and weight and as such should be able to be packaged in an area other than the passenger foot well.

Within the vehicle integration activities, it was possible to implement an innovative control system that latched the boost demand when both the boost button and the clutch pedal were pressed. This allowed a torque demand to be sent to the motors when the throttle pedal was released, motoring the vehicle through the gear changes. Further innovation was realised through not utilising regenerative braking, leading to a system with a limited amount of energy for the driver to use throughout the race.

14 DISCUSSION

14.1 Overview

The use of hybrid electric vehicles in motorsport has evolved rapidly since the start of this project in 2006. This has occurred in two main areas, professional motorsport, such as Formula One and the Le Mans series of endurance races, and student led motorsport, such as Formula Hybrid and Formula Student Class 1A. In comparison, club motorsport has seen no development and there represents an opportunity for innovation.

One reason for this may be due to the different ways in which these types of motorsport are funded. A typical budget for a Formula One team, including the drivers, mechanics and engineers, is approximately £300,000,000 a year [110]. The budgets for student led racing are much smaller, with the majority of finance coming from sponsorship and university funding. While the students are not paid for taking part, participation in the event usually counts towards their studies. Club motorsport is different in that the majority of the funding is personally paid for by the owner/driver of the vehicle, making this form of motorsport much more risk adverse and less likely to invest in new environmentally friendly technology.

Therefore, to implement hybrid electric vehicle technology into club motorsport, the requirement is on the vehicle manufacturers to take on this risk and invest in the technology. As few club motorsport manufacturers have experience in hybrid electric vehicle design and with increasing pressure for all industries to be more environmentally friendly, this puts club motorsport industry at risk of becoming irrelevant. This project addresses this by identifying an innovative solution the problem.

14.1.1 System Requirements

Investigations into the customer requirements for such a system showed that the performance of the vehicle was the most important factor. In addition, it was seen that a hybrid petrol drivetrain could be as accepted as a conventional petrol drivetrain. This indicates that consumers are open to drivetrain developments, provided there is a benefit to performance, and that there is a market for an appropriate hybrid electric vehicle in the club motorsport industry.

It was also shown that the power of the vehicle was not important. An argument commonly used by the industry for not introducing hybrid and electric vehicle technology into club motorsport has been that it is difficult to compare the performance of an electric motor to an internal combustion engine and this may discourage potential customers. An electric motor has a high starting torque that reduces once the motor enters its constant power phase at higher speeds. In comparison, an internal combustion engine will typically produce peak torque at higher engine speeds. The result of this is that whilst the two drivetrains might have a similar overall performance, the maximum power figure for the electric motor will be lower. This was seen in the customer survey where engine power received a high importance. However, this project challenges this assumption through the innovative use of conjoint analysis. When customers were presented with a choice between engine power and acceleration time, the importance of engine power was much reduced. This indicated that, contrary to industry assumptions, 0 to 26.8ms^{-1} (0-60mph) acceleration time is of higher importance than engine power.

0 to 26.8ms^{-1} (0-60mph) acceleration time was also identified by the supporting company of being of high importance. Developing a system around lap time improvements would make the performance gains difficult to convey to potential customers. In comparison, a class leading 0 to 26.8ms^{-1} (0-60mph) acceleration time would make it easy for the customer to realise the performance benefits of the hybrid drivetrain over conventionally fuelled vehicles, as shown in the conjoint analysis. Therefore, a 0 to 26.8ms^{-1} (0-60mph) acceleration time of 3 seconds became the primary design target. Developing the drivetrain around fuel economy gains would have resulted in a drivetrain that did not meet the requirements.

The customer survey also asked the participants whether they would require a number of optional extras. While these optional extras are seen as desirable upgrades to most road vehicles, the customer survey showed that the UK niche sports car market has very different priorities. Even with no degradation in vehicle performance, these optional extras scored poorly, probably because by using these optional extras, control is taken away from the driver. It was therefore important that the developed hybrid system allowed the driver to remain fully in control of the system. It is worth noting that this is in opposition to the 24 Heures du Mans regulations, which state the engine and electric motor must be controlled together through the accelerator pedal, with direct control of the hybrid drivetrain, through a push to pass system, strictly forbidden.

Due to the lack of driver control, series hybrid architectures were not deemed suitable for this system. Further investigation into a number of parallel and combined hybrid architectures was then undertaken. Simulations showed that, while quicker acceleration times were available with other architectures, a through-the-road parallel hybrid architecture gave the greatest benefit in 0 to 26.8ms^{-1} (0-60mph) acceleration time, taking into account the amount of electric power utilised on the vehicle. This investigation presented an opportunity for innovation through the development of a method of determining, through a new equation, the benefit that the hybrid architecture gave, given the amount of electric power available. This has been named the Benefit Factor equation.

14.1.2 System Design

Through-the-road parallel hybrid architectures have only been used in a few road vehicles, with the majority of mass produced hybrid electric vehicles being combined hybrids, such as the Toyota and Lexus hybrid models [31] and the Chevrolet Volt (whilst the Chevrolet Volt was originally advertised as a range extended electric vehicle, at high speed the engine is used to assist propulsion, making it a combined hybrid) [111]. One reason why through-the-road parallel hybrid architectures have not become popular in mass produced hybrid electric vehicles may be due to the complexity of controlling the systems. However, this issue is no longer relevant if the driver is given control over when and how the hybrid system is used, as in the system designed for this project, with this complexity being used to give the driver extra enjoyment. Furthermore, the main advantage of a through-the-road parallel hybrid architecture is the additional traction that can be used. This provides an advantage for performance orientated systems, but is not as relevant for the fuel economy orientated systems installed on most road hybrid electric vehicles.

A small number of Formula Student teams have attempted to implement through-the-road parallel hybrid electric vehicles. However the constraints put upon them by the chassis regulations make it difficult to package electric motors to drive the vehicles. Of the hybrid electric racing cars that have competed in the Le Mans series of event, one of the most successful has been the Porsche 911 GT3 R which was also a through-the-road parallel hybrid vehicle.

One disadvantage of using a through-the-road parallel hybrid architecture on a previously rear wheel drive racing car, is the need to provide drive to the front wheels. It has been shown through simulation that this extra traction provides a larger benefit than systems without the front wheels driven on a previously rear wheel drive racing car. It is this additional performance benefit that maximised the acceleration that could be achieved, that meant that a through-the-road parallel hybrid architecture was chosen for this drivetrain.

Drive to the front wheels can either be achieved with one electric motor acting through a differential or two electric motors independently driving each wheel. Running with two motors has the advantage of not requiring a differential but introduces the risk of the motors providing different levels of torque to the wheels, destabilising the vehicle. With additional control, this risk can be exploited and torque vectoring can be realised (where different levels of torque are given to the wheels to aid cornering). However, as the results of the requirements analysis has shown that customers generally do not want extras that take control away from the driver, the use of torque vectoring may not be appropriate for this application.

Of the 48 motor options that were simulated, a dual motor option, based on the Oxford YASA Motors dual motor system, was shown to give one of the quickest 0 to 26.8ms^{-1} (0-60mph) acceleration time, 3.648s. Furthermore, this motor option combined the most packagable option with a high availability for the motor. This configuration was then used as the basis of an analysis into the suitability of energy storage devices and the effect of battery size on performance.

While an ultracapacitor based system may seem the obvious choice for a hybrid electric drivetrain whose main design aim was to provide sufficient boost to increase acceleration to close to 3s, the study showed that ultracapacitor systems are too heavy and, as such, are not suitable for use in a lightweight motorsport application. In comparison, a lithium ion battery was shown to provide the same power, for a longer time and a lower mass. However, the literature provided by the battery manufacturers was not sufficient enough to design a battery pack and further testing was required.

Testing of the cells showed that each cell had an average maximum constant power of 129W. While higher powers are possible, running at this power means that the cell cannot go into an over-temperature condition. At 129W, the battery would require at least 600 cells to provide a constant power of 80kW. However, it was seen that this peak power was not required to meet the 0 to 26.8ms^{-1} (0-60mph) acceleration times and that by reducing the system to 400 cells, reducing both the weight and cost of the system, the acceleration dropped by just 0.11s to 3.878s. Therefore, a battery of 396 cells, 3 in parallel, 132 in series, was determined to be the optimum number to provide power to the hybrid electric system.

This battery was split into two packs and was mounted underneath the seats of the car. This allowed the weight of the battery to be kept low down in the vehicle, reducing any negative effects on handling. The battery was housed in a rapid prototyped case that was designed to allow air flow around the individual cells. The aim of this was to cool the cells so that, if in vehicle testing showed it possible, additional power could be drawn from the battery.

Rapid prototyping was used for the battery housing as it would not be possible to use more conventional methods to machine or injection mould the features that allowed air to flow around the cells. Whilst suitable for prototype use, or as a high cost weight saving option, a rapid prototyped battery case would not be suitable for a production based system as it would be cost prohibitive. A more suitable solution for a limited production of batteries (around 200 per year) would be a fabricated aluminium box.

14.1.3 Inverter Testing

During testing, it was found that the inverters were not suitable for the application as one of the motors was uncontrollable and there was a low speed torque creep effect. This was due to the software not being fully tested or completed, despite extensive on the bench testing by Oxford YASA Motors. The engineer who developed the inverter software had since left the company leaving this software unsupported. Following an incident where another prototype vehicle caught fire (the vehicle was using the same inverter and software, with the blame placed on a failure within the inverter), the company discontinued support for the inverter. Therefore replacement inverters would be required, a major requirement for these inverters being their ability to be packaged into a small space. Figure 52 shows an example of a possible packaging space for the inverters (to the side of the engine bay), now in use with Oxford YASA Motors. These new inverters are not compatible with the existing battery system, as their maximum voltage is lower than the existing battery voltage.

The original inverters had seen extensive on the bench testing, which included the simulation of real world drive cycles in an attempt to simulate their operation on a vehicle. However, this testing has been proven insufficient in simulating real world applications.

Testing of the inverters could be achieved through the installation of the new inverters in a temporary location on the vehicle (for example in the driver's seat), and having these inverters cabled to the motors. The motors would need to be swapped for motors with the correct position sensors and a new power source would be required. It is possible that this could be with an external power supply, with some testing on a rolling road. However, to fully accept the inverters as suitable, some basic dynamic testing of the vehicle would be necessary.

As the maximum voltage of the new inverters would be below that of the existing battery system, a lower voltage power source is required. This could be achieved by using only half of the battery system (one pack), to give a battery with a maximum voltage of 237.6V. This voltage may not be sufficient to prove the maximum performance of the entire system, but it would be sufficient to test the on vehicle behaviour of the motor/inverter combination and justify redesign of the battery system.

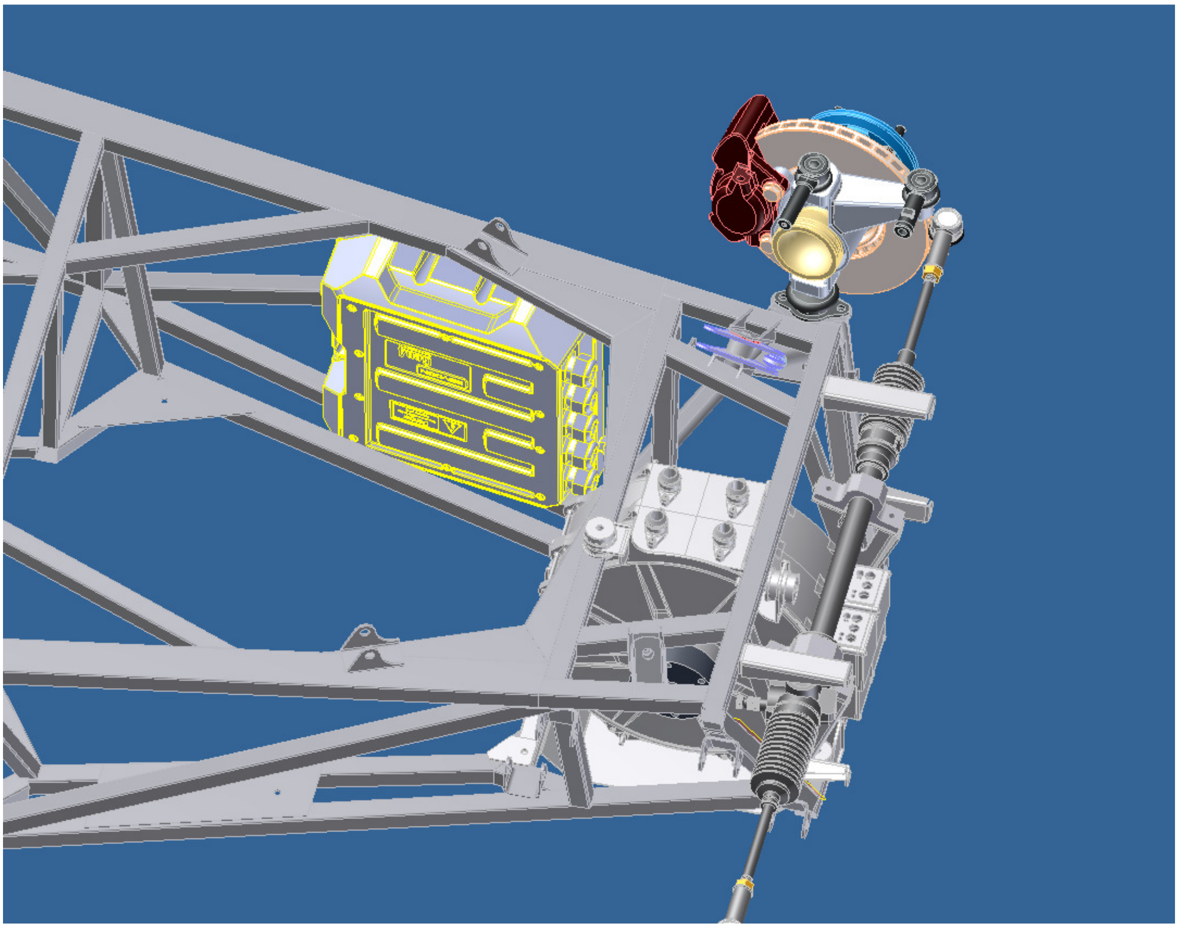


Figure 52. Possible New Inverter Location

14.1.4 System Integration

Whilst some modification to the standard Westfield Sportscars Sport Turbo chassis was required, a major redesign of the chassis was not required. This relative ease of installation would suggest that there is the possibility to retrofit the hybrid drivetrain to existing vehicles, which could have a vast impact, given the number of Westfield Sportscars vehicles that are currently in use. However, additional work on developing a retro fit kit would be required. The only integration issue that was not resolved was the packaging of the inverters as these were installed in the passenger foot well in the prototype vehicle. To take this vehicle to production, new inverters would be required and would need integrating within the vehicle.

It was discussed in the literature review, that, to retain the driver enjoyment, one of the project requirements, there should be high levels of longitudinal and lateral acceleration. Whilst the system has been shown to be able to increase the longitudinal acceleration of the vehicle, no analysis of its effect on lateral acceleration has been carried out. To reduce the chance of a negative impact on longitudinal acceleration, the mass of the system was kept as low as possible and the components distributed in a low position in the car. Whilst there has not been a full study of the handling, Paul Faithfull, the Managing Director of Potenza Technology and Technical Director of Westfield Sportscars, was happy with the vehicle's handling performance, with the hybrid drivetrain in place, following a test drive.

Given the compact size of the motors and battery system, it is also possible that the system could be packaged and used in other vehicle platforms, such as the GTM Sports Cars platform owned by Potenza Sports Cars. The parameters for a GTM Libra Touring 2500, shown in Table 37, were input into the vehicle simulation tool and it was found that the hybrid drivetrain reduced the 0 to 26.8ms^{-1} (0-60mph) acceleration from 5.998 seconds to 3.805 seconds. Inputting this into the conjoint analysis market simulation tool, it was found that 49% of people would choose the hybrid GTM Libra over the standard vehicle. The parameters used are shown in Table 38.

Vehicle Parameters	**Parameter Value**
Base Vehicle Mass (kg)	830
Energy Storage Mass (kg)	60 (including all associated components)
Gearing Mass (kg)	0
Motor Mass (kg)	30 per motor utilised
Tyre Rolling Radius (m)	0.275
Final Drive Ratio	3.94
Gear Ratios	[3.58 2.02 1.35 1.03 0.81]
Engine Torque (Nm)	[180 215 230 245 235 220 200]
Engine Speeds (rads^{-1})	[105 209 314 419 524 628 707]

Table 37. GTM Libra Touring 2500 Vehicle Parameters

Attribute	**GTM Libra Touring 2500**	**GTM Libra Hybrid**
Engine Power	200 BHP	300 BHP
Acceleration Time	5 s	4 s
Fuel Economy	25 MPG	30 MPG
Drivetrain Type	Conventional Petrol	Hybrid Petrol
Price	£25,000	£35,000

Table 38. GTM Libra Hybrid Attributes

This shows that, providing that the system can be mechanically integrated into a GTM Libra vehicle chassis, there is scope for the hybrid drivetrain to also be used in GTM products. The ability of this system to be used in other vehicles is unique and has the potential to aid other similar vehicle manufacturers to offer systems that are both attractive to customers and are seen as environmentally friendly.

14.1.5 Effect on Handling

Throughout this project, the effect this drivetrain could have on handling has not been investigated in detail. The supporting company, Potenza Technology, specified that the main aim of the project should be the acceleration time. While this was partly motivated for performance reasons, it was also partly motivated by commercial and marketing reasons because it is easier to sell an impressive acceleration time than an increase in handling that cannot be easily quantified.

The aim of reducing the acceleration time was so important to the supporting company, that it was even specified that the handling of the vehicle could be made slightly worse as a result of integrating the hybrid drivetrain as long as the effect is not so large that it makes the vehicle unenjoyable to drive. This was because the intention was to have a single make race series, where all the vehicles have the same drivetrain. If there was an effect on the handling, then as long as it wasn't noticeable during driving it would not be a problem because the car would not be competing against standard vehicles and comparison could not be made.

However efforts were taken to reduce the effect on handling as far as possible. For example, the motors were placed in the middle of the chassis centre line, to not affect lateral mass distribution. The batteries were placed under each seat, to not affect the lateral weight distribution and be as low as possible to not raise the centre of gravity of the sprung mass. The inverters were unable to be mounted centrally, so were mounted in the passenger foot well as their weight could help offset the driver. The suspension was changed to an inboard suspension type, which would reduce un-sprung mass and could aid the vehicle's handling ability.

However, while the motors were on the vehicle centre line, they were mounted at the front of the vehicle and are likely to move the longitudinal mass distribution forward. The effect of this could reduce how well the car handles.

Furthermore, the drive to the front wheels from the motors could introduce the problem of torque steering. The impact of this was reduced through the motor mount design, equal length half shafts and equal torque requests between left and right motors. As further work, torque steering can be used to aid handling through the correct changes in torque distribution between left and right, using a principle know as torque vectoring [109, 112]. This was not investigated in this project, but could be investigated as part of future work.

During the development phase the vehicle was driven by experienced Westfield Sportscars Employees and the Managing Director of Potenza Technology, without the hybrid system activated, but with the components installed. The vehicle was raced up the hill climb circuit at the Goodwood Festival of Speed and whilst the main objective for the event was publicity, none of the drivers were able to notice any negative impact on vehicle handling..

14.2 Dissemination

As a result of this project, a prototype vehicle was built. Due to circumstances out of the control of this project, full testing was unable to be completed. However, the vehicle was exhibited at the Goodwood Festival of Speed in July 2010, with a fully integrated hybrid drivetrain running on ICE power only. The informal feedback that was received was positive, with members of the public, motoring press and motorsport industry expressing interest in the drivetrain. Figure 53 shows the vehicle taking part in one of the hill climb events at the Goodwood Festival of Speed.

As a result of the publicity generated by the Goodwood Festival of Speed, an article was published in a trade magazine explaining how rapid prototyping was used for this project [113]. A news article was also posted by Race Tech International magazine on their website, explaining the system [114].

The work of this project has been presented at two international conferences [102, 115] and has also resulted in the acceptance of a peer reviewed paper into The International Journal of Environmental, Cultural, Economic and Social Sustainability [97]. Copies of these papers and articles can be found in Submission 6 of this Engineering Doctorate [9].

Figure 53. Hybrid Westfield at the Goodwood Festival of Speed 2010

14.3 System Feasibility

The design and build of a prototype vehicle has shown that a hybrid electric racing car, based on a Westfield Sportscars Sport Turbo is technically possible. However, for the system to become commercially viable in production, it must be financially feasible. Based on a production of 200 systems a year, the approximate costs for the system are shown in Table 39. The Potenza Technology/Westfield Sportscars margin has been calculated according to the specification in Submission 2 of this Engineering Doctorate [5]. Costs for the motor have been taken from the motor manufacturer's cost projections for the motor in mass production [116].

The over £10,000 additional cost is in excess of the original estimate by Potenza technology. However the results of the conjoint analysis showed that at an additional cost of £10,000, 49% of people would choose a hybrid variant over a conventionally fuelled Westfield Sportscars Sport Turbo. This only drops to 45% for £15,000, which would give Potenza a larger margin. While the drivetrain requires additional work to see it reach production level, this project has proved that the system could be feasible in production of 200 units a year.

Item	Cost	Quantity	Total
Motor and Inverter	£1200	2	£2,400.00
Battery Cells	£5	400	£2,000.00
Battery Casing, BMS, Contactors, Fuses	£500	2	£1,000.00
Harnesses	£200	1	£200.00
Dielectric Coolant, Pumps, Pipes	£200	1	£200.00
Unit Cost			**£5800.00**
Potenza Technology/Westfield Sportscars Margin and Fitting			£3248.00
VAT (at 20%)			£1809.60
Total			**£10,857.60**

Table 39. Hybrid Drivetrain costs in Production

14.4 System Requirements

During the requirements analysis, a number of requirements were specified by the supporting company. These requirements were split into wants and needs, depending on the importance that Potenza Technology, the supporting company for this project, placed on each requirement. A list of the requirements, detailing whether each requirement has been met during the course of this project, is shown in Table 40.

It can be seen that all of the requirements have been met with the only exceptions being the acceleration of the vehicle and the price. Through simulation it was shown that it was not possible to use an off-the-shelf motor to achieve a 0 to 26.8ms^{-1} (0-60mph) acceleration time of 3 seconds, with development of a new motor out of the scope of this project. However this drivetrain did reduce 0 to 26.8ms-1 (0-60mph) acceleration time by 1.6 seconds compared with a standard Westfield Sports Turbo. While the system costs have proved to be higher than originally required by Potenza Technology, it has been shown in the conjoint analysis that they are likely to be acceptable to the customer.

Requirement	Type	Met	Comments
Work with all cars Potenza Sports Cars sell	Want	Yes	System is drivetrain independent, however will depend on packaging of vehicle
Work with Westfield Sportscars SE models	Need	Yes	
Can be retro-fitted to old Westfield Sportscars SE models	Want	Yes	With modifications to chassis
Is an electric hybrid	Need	Yes	
Uses the same parts as the electric vehicle currently being developed	Want	Yes	Uses same motors
Driver remains in control of the vehicle and the hybrid system	Need	Yes	
Can be used on the race track	Need	Yes	May require certification to FIA regulations
Can be used on the road	Want	Yes	May require compliance with ISO6469
Increases vehicle acceleration	Need	Yes	
Westfield Sportscars SE to achieve 0 to 26.8ms^{-1} (0-60mph) in 3 seconds	Want	No	3.878s predicted 0 to 26.8ms^{-1} (0-60mph) time
Hybrid system allows optional extras, such as boost or ABS.	Want	Yes	There is the potential to implement this, however customer survey has shown this is not required
System must be safe	Need	Yes	With replacement inverter
Parts are not user serviceable	Need	Yes	
All components are sealed to protect users from accessing internals	Need	Yes	
Retail price below £8,000	Want	No	Price is still within acceptable price according to conjoint analysis
Unit cost of £4,500	Want	No	Price is still within acceptable price according to conjoint analysis

Table 40. System Requirements

14.5 Innovation

In professional motorsport, series regulations restrict the opportunities for innovation, particularly around environmentally friendly technology. The Managing Director of Williams Hybrid Power (who developed the hybrid drivetrain for the Porsche 911 GT3 R hybrid) has suggested that professional motorsport should aim towards deregulation as, over the last 10 years, motorsport has become increasingly prescriptive, stifling innovation [117].

This project is the first, and so far only, effort to introduce hybrid electric vehicle technology into the club motorsport market. The advantage of using club motorsport to develop this hybrid electric drivetrain was the lack of series regulations, constraining the design. It is this approach that has enabled an innovative hybrid drivetrain for club motorsport to be developed. From this project there have been two main innovations, the innovation in the hybrid drivetrain and the innovation in the process that led to the drivetrain.

14.5.1 Hybrid Drivetrain Innovation

This project represents the first time that hybrid electric vehicle technology has been successfully implemented in club motorsport. Some of the features of this implementation are innovative, not only in club motorsport, but in the wider motorsport and mainstream automotive industries. It has been shown that the innovative hybrid drivetrain has the ability to reduce 0 to $26.8ms^{-1}$ (0-60mph) acceleration time from 6.38 seconds to 3.85 seconds.

To achieve this, the system made use of a through-the-road parallel hybrid architecture, which gave the vehicle four wheel drive. The advantages of four wheel drive, such as increased levels of traction, are well known in motorsport. However, implementing it in motorsport has always been difficult as it typically requires complex, heavy and costly mechanical transfer of drive around the vehicle and is rarely implemented well. In a hybrid drivetrain, these issues are not a problem as the mechanical connections are replaced with electrical connections. A through-the-road parallel hybrid architecture was implemented on the Porsche 911 GT3 R Hybrid, which has competed in professional endurance racing; however it has never been implemented in low cost club motorsport.

An advantage of the through-the-road parallel hybrid architecture is the ability for the drivetrain to be platform independent, requiring only mechanical modifications to package. This innovation could have significant impact on the club motorsport industry. Without investment in to alternative drivetrain, the industry is at risk of becoming irrelevant. With the majority of companies in this industry not having the funding or resources to develop these systems, a ‘shelf engineered’ hybrid drivetrain that can be used on other platforms owned by Potenza Sports Cars as well as other niche vehicle manufacturers platforms, may provide an answer to this problem as well as providing additional income for Potenza Technology.

The ability for the drivetrain, in a through-the-road parallel hybrid architecture, to be able to drive independently of the engine has provided the opportunity for an innovative driver control system. When a boost is requested, the torque demand for the electric motors is tied to the throttle pedal position. However, when the clutch is pressed, the torque demand to the motors is latched, allowing the driver to release the throttle pedal to change gears whist also keeping the motors driving through the gear change. This innovation contributes to the overall reduction in 0 to $26.8ms^{-1}$ (0-60mph) acceleration time.

The operation of the system is innovative and unique to the motorsport industry as well as the mainstream automotive industry. As there were no defined control requirements, the energy storage system was chosen purely on its ability to provide the required power in a low mass. Due to the inability of the system to rapidly recover braking energy and it's comparably large energy content, a system by where the driver is given a set amount of boost energy for a race was developed. As well as bringing push to pass to club motorsport, an additional level of strategy is brought in as the driver can choose exactly when and where in the race the energy storage is used. Whilst in Formula One and the Le Mans series of races, this form of energy management is prohibited, Ross Brawn, team Principal at the Mercedes Formula One team, has said "If we had a push-to-pass button that you could use only a certain amount of times, then we would have something quite exciting" [118]. At present, in Formula One, KERS functionality is being provided by lithium ion battery systems that would be better suited, due to their limited charge rates, to an alternative control strategy.

14.5.2 Benefit Factor

New technologies, such as hybrid electric vehicles have not seen the same level of development as conventional drivetrain technologies. For this reason, the understanding of these technologies is not pervasive within the motorsport industry, unlike conventional drivetrain technologies. Benefit Factor provides a method of comparing hybrid drivetrains in terms of performance.

The benefit factor metric therefore provides a mechanism for ascertaining the most efficient architecture in terms of electrical power employed against improvement in acceleration performance. This represents an innovation as, whilst providing a drivetrain solution that has maximum performance, utilising too much additional extra electrical power is likely to result in a drivetrain that is both expensive and costly and unlikely to be commercially viable.

14.5.3 Process Innovation

The process that led to the design of the hybrid drivetrain was also innovative. Unlike other hybrid vehicles in motorsport, the design process did not use the regulations of a given race series as a starting point, but used the overall requirements of the system, gathered in an academic and rigorous fashion. This resulted in a solution that met both the technical and commercial requirements of the system. This is important for the club motorsport industry which, unlike the professional motorsport sector, relies on selling vehicles to members of the public.

The design process, consisting of four phases, each phase having three steps, the completion of which will lead to a deliverable, is shown in Figure 54. The activities that were carried out in each step are shown in Table 41. After each phase of the process there was an output that was used to aid the design of the drivetrain throughout the rest of the project. The outputs for each stage are shown in Table 42, the along with the output found during the project.

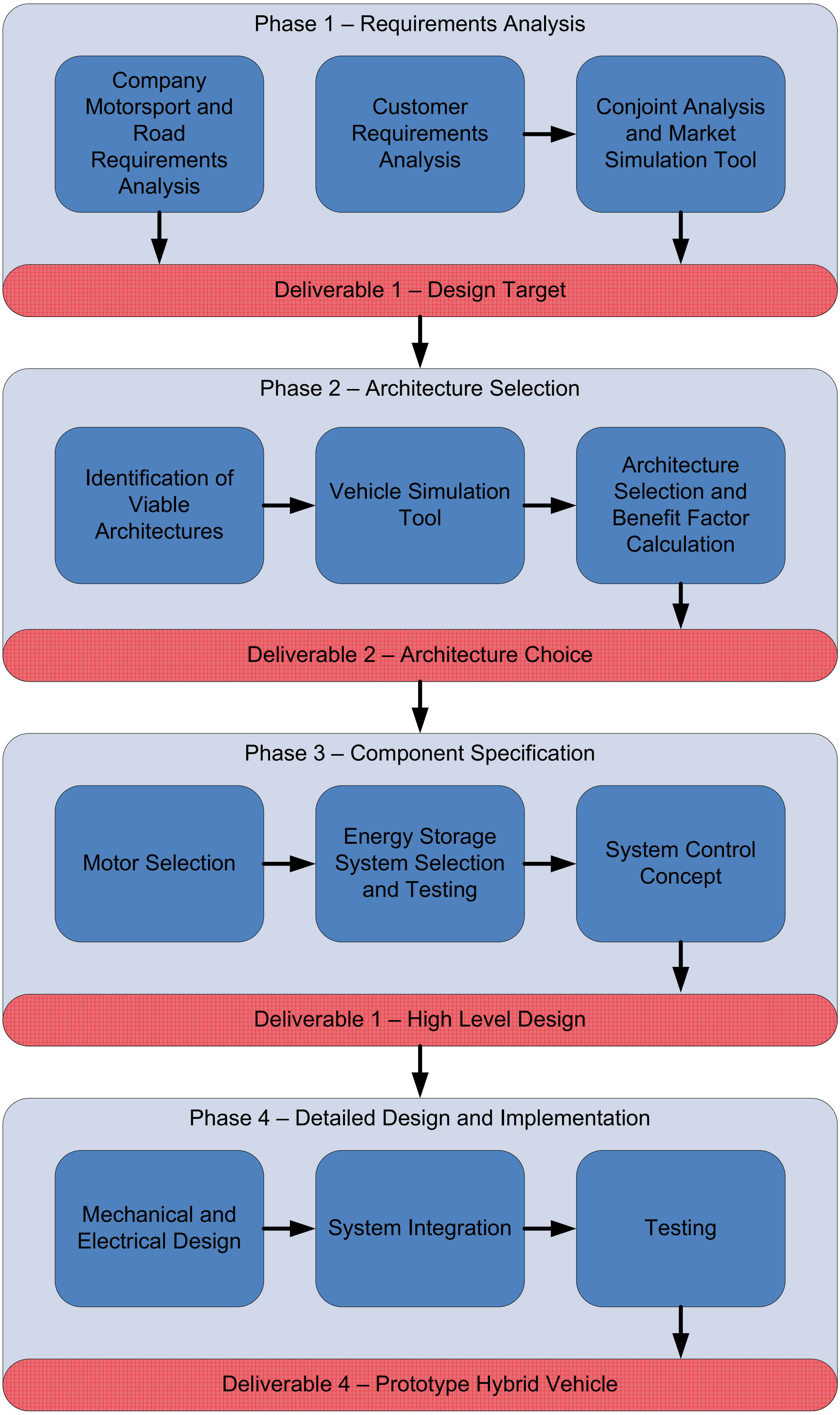


Figure 54. Design Process for Hybrid Vehicles in Club Motorsport

Step	Activity
Company, Motorsport and Road requirements Analysis	Determination or company, road and motorsport requirements
Customer Requirements Analysis	Customer survey to understand identify key requirements
Conjoint Analysis and Market Simulation Tool	Conjoint analysis to understand complex customer requirements and tool to simulate price points of different configurations
Identification of Viable Architectures	Analysis of available architecture options
Vehicle Simulation Tool	Development of a tool to simulate the performance of the vehicle
Architecture Selection and Benefit Factor Calculation	Use of simulation tool to compare different architectures and analysis using benefit factor calculation
Motor Selection	Use of simulation tool to compare the effect of different motors
Energy Storage System Selection and Testing	Selection of energy storage system and testing of selected system
System Control Concept	Design of system control concept based on requirements and energy storage system
Mechanical and Electrical Design	Design and packaging of the system within the vehicle
System Integration	Design of the control system and integration with the existing vehicle
Testing	Testing of the vehicle against the requirements

Table 41. Design Process Steps

Phase	Output	Project Output
Phase 1	Design Target	0-60 mph acceleration time of 3 seconds
Phase 2	Architecture Choice	Through-the-road parallel hybrid architecture
Phase 3	High Level Design	Lithium ion battery, dual motor drive with set boosts
Phase 4	Prototype Vehicle	Hybrid Westfield

Table 42. Design Process Phase Outputs

The main difference between this process and a process followed for other forms of motorsport is the work involved in Phase 1, Phase 2 and Phase 3. For example, in Formula One the regulations have predetermined the deliverables for Phase 1, Phase 2 and the System Control Concept step in Phase 3. Formula Hybrid allows more flexibility, but the system requirements found in Phase 1 have been predetermined by the regulations and the scoring structure.

It is worth noting the significance of the Benefit Factor calculations in the process. If there are no regulations to follow, in the interest of achieving increased performance, excessive hybridisation could occur. The new Benefit Factors calculation provides a method of restricting excessive hybridisation, resulting in a system more likely to meet the cost and complexity requirements.

The use of conjoint analysis, a first for this industry, showed that the tendency of vehicle manufacturers to primarily quote engine power figures may not be the best use of the vehicle attributes in the club motorsport market. With a closer relationship to driver enjoyment, 0 to $26.8ms^{-1}$ (0-60mph) acceleration was shown to be of higher importance and became the design target deliverable from Phase 1.

Following this process through, allowed an innovative hybrid drivetrain to be developed that met both the commercial requirements of the industry and the technical requirements. Without this process, it may have been tempting to develop a hybrid drivetrain based on that used in other forms of motorsport. This would have resulted in a drivetrain that was not innovative and not optimised for the club motorsport industry.

There is also scope to extend the use of this process out of club motorsport and into other forms of motorsport. To do this would require the deregulation of hybrid electric vehicles in these other forms of motorsport to allow vehicle manufacturers to develop their own innovative drivetrains. This would allow the process to further the development of hybrid electric vehicles in motorsport sectors, other than club motorsport.

Furthermore, the process could be used to develop innovative hybrid vehicles in the wider niche vehicle industry and the mainstream automotive industry. Whilst the current focus for the design of most road going vehicles is the reduction of CO_2 output, many vehicles operating in the niche vehicle industry (and the mainstream automotive industry to some extent) are not as concerned with this requirement. Following this process, ensuring that the system requirements are well understood and followed, could result in new and innovative hybrid drivetrains being developed.

14.6 Company Impact

This project has also had significant impact on the supporting company, Potenza Technology. In 2008, as a direct result of the work carried out on the hybrid race car project, Potenza Technology started work on an electric race car based on the Westfield Sportscars chassis, known as the iRacer. To develop this drivetrain, the results of the customer survey and conjoint analysis, carried out as part of this Engineering Doctorate, were used to develop the business case for this car. The vehicle simulation tool, also designed as part of this Engineering Doctorate, was then used to analyse the design options available. As a result of its use on the hybrid prototype, the iRacer uses the same Oxford YASA Motors dual motor system and the hybrid vehicle. The iRacer now had its own vehicle class in the EV Cup electric vehicle race series, with a small fleet of road going vehicles also under fleet test.

15 CONCLUSIONS

The aim of this project was to develop an innovative hybrid electric vehicle drivetrain suitable for use in club motorsport. Through a process of requirements analysis, simulation, testing and design, a hybrid electric drivetrain was successfully integrated into a Westfield Sportscars Sport Turbo vehicle, resulting in the build of the first hybrid electric vehicle designed for club motorsport. The main findings of the project are:

- Customers in the club motorsport industry are receptive to alternative drivetrains as long as they produce an increase in driver enjoyment, with almost no preference shown for conventional petrol drivetrains over hybrid petrol drivetrains.

- A through-the-road parallel hybrid architecture provides the greatest benefit to a club motorsport vehicle, in terms of 0 to 26.8ms^{-1} (0-60mph) time decrease and electric power utilised.

- High power lithium-ion battery systems provide a better mix of specific power and specific energy then ultracapacitor systems for club motorsport applications.

- It is possible to package a hybrid drivetrain, capable of achieving a 0 to 26.8ms^{-1} (0-60mph) acceleration time of less than four seconds, within the chassis constraints of a club motorsport vehicle, in this case a Westfield Sportscars Sport Turbo.

- The cost of producing a hybrid electric drivetrain for use in club motorsport market is not cost prohibitive.

- A design process for club motorsport manufacturers, primarily focused on increasing vehicle performance over meeting race series regulations, has been shown to produce designs closer to the customer requirements.

These findings have resulted in the development and implementation of an innovative hybrid drivetrain for club motorsport. The main innovations contained within this system are:

- A drivetrain that enables the advantages of four wheel drive to be realised in club motorsport through the use of a through-the-road parallel hybrid architecture.
- A 'shelf engineered' hybrid system that could be used on other platforms owned by Potenza Sports Cars as well as other platforms in the niche vehicle industry.
- A driver control system that allows the hybrid drivetrain to drive through gear changes, whilst leaving the driver in control. It is important that this level of driver control is retained in hybrid drivetrains in the club motorsport and niche vehicle industry.
- A system operation by where the driver of the race car is given a set amount of energy for a given race and is able to decide how and when the energy is used in the form of short boots. This has application in both the club motorsport sector as well as the wider motorsport industry.
- A process that makes use of a lack of predefined requirements, in the form of technical regulations, to determine the optimum hybrid electric vehicle design for a given type of motorsport and niche vehicle. This process makes use of innovations in conjoint analysis and Benefit Factor
- The use of conjoint analysis to fully understand the customer requirements and enable the creation of a design target that will meet these requirements.
- The use of the Benefit Factor calculation to ensure that the designs for hybrid electric vehicles for motorsport and the niche vehicle industry make the most efficient use of additional electric power.

15.1 Future Work

This project has been successful in proving the concept of a hybrid electric vehicle for use in club motorsport and in being innovative within the motorsport industry. However, further work is required to take the prototype through additional testing and into production.

15.1.1 Inverters

Due to the failure of the inverters originally used, further work should be carried out with alternative inverters. Initial tests could be carried out using half of the existing battery system to ensure that the battery voltage is within the inverter operating range. If successful, a redesign of the inverter integration and of the battery pack would be necessary to enable full dynamic testing of the prototype.

15.1.2 Dynamic Testing

With the inverters working correctly and safely, full dynamic testing of the prototype vehicle could be continued. The aim of this testing would be to test the function of the system, refine the integration and control of the system. It would also include dynamic testing to prove the acceleration of the vehicle and the effects of the hybrid drivetrain in a racing situation.

15.1.3 Battery Thermal Testing

It would be possible to realise more power from the battery system, if higher peak powers were available. There is a risk that this could introduce issues with the batteries overheating and the system having to de-rate. However, the cooling efficiency of the battery system and the cell housing is unknown, as well as the heat generation in the batteries under race conditions. Analysis of the prototype vehicle test results would provide information on the actual temperature rise in the cells and would also provide information on typical drive cycles in a race condition. These drive cycles could then be used to investigate the effect of increasing the maximum power available through simulation, before further testing on the vehicle.

15.1.4 Regenerative Braking

The effect of regenerative braking could be investigated further to analyse both the advantage in additional energy available and the disadvantage in additional heat generation from high charge currents. With representative drive cycles, this could be simulated, before implementing on the vehicle for testing and an indication on whether there is likely to be a benefit in introducing regenerative braking can be established.

15.1.5 Customer Survey and Conjoint Analysis

The Customer Survey and Conjoint analysis were carried out in 2007. At this time, there were no hybrid electric vehicles actively involved in motorsport. Since 2007, there has been significant development in hybrid electric vehicles for motorsport and as a result it is likely that customer opinions are likely to have changed. An understanding of how these consumer attitudes have changed could be attained through a further survey and conjoint analysis and comparing against the results obtained during this project. This would further aid in the commercial aspects of the project, such as re-establishing the market and setting appropriate costs.

15.1.6 Quantification of Effects on Handling

The effects on the handling system of the hybrid drivetrain have not been quantified. Back to back testing by an expert driver of a standard vehicle and a vehicle with the hybrid drivetrain installed would provide quantifiable information on any effect handling by the system. This could be supplemented with additional simulation work to investigate how these effects can be altered through the changing of parameters such as suspension set up and weight distribution. One the effect is known, if it is a problem, it can then be altered through further drivetrain design or suspension setup.

16 REFERENCES

1. Ozaki, R. and K. Sevastyanova, Going hybrid: An analysis of consumer purchase motivations, Energy Policy, 2010, 39(5), pp. 2217-2227.

2. Sekimori, T., Development of Toyota's electric and hybrid vehicle, SAE paper 98C053.

3. European Commission, Recommendation 2003/361/EC: SME definition. 6th May 2003.

4. Lambert, S., Engineering Doctorate Submission 1, Literature review, Advancing the Development of Hybrid Electric Vehicles in Motorsport, University of Warwick, 2009

5. Lambert, S., Engineering Doctorate Submission 2, Requirements capture and analysis, Advancing the Development of Hybrid Electric Vehicles in Motorsport, 2009

6. Lambert, S., Engineering Doctorate Submission 3, Identifying the design parameters for a hybrid electric racing car through simulation, Advancing the Development of Hybrid Electric Vehicles in Motorsport, 2010

7. Lambert, S., Engineering Doctorate Submission 4, Battery system analysis and testing, Advancing the Development of Hybrid Electric Vehicles in Motorsport, 2010

8. Lambert, S., Engineering Doctorate Submission 5, Integration of a high performance hybrid electric drivetrain for motorsport, Advancing the Development of Hybrid Electric Vehicles in Motorsport, 2011

9. Lambert, S., Engineering Doctorate Submission 6, Published papers and articles, Advancing the Development of Hybrid Electric Vehicles in Motorsport, 2011

10. Ehsani, M., G. Yimin and J.M. Miller, Hybrid electric vehicles: architecture and motor drives, Proceedings of the IEEE, 2007, 95(4), pp. 719-28.

11. Gao, Y., M. Ehsani and J.M. Miller, Hybrid electric vehicle: Overview and state of the art, IEEE International Symposium on Industrial Electronics, 2005, Institute of Electrical and Electronics Engineers.

12. Ehsani, M., Y. Gao, S. Gay and A. Amade, Modern electric, hybrid electric, and fuel cell vehicles : fundamentals, theory, and design, 2005, CRC Press.

13. Chan, C.C., The state of the art of electric and hybrid vehicles, Proceedings of the IEEE, 2002, 90(2), pp. 247-275.

14. Lo, E.W.C., Review on the configurations of hybrid electric vehicles, Power Electronics Systems and Applications, 2009. PESA 2009. 3rd International Conference on, 2009.

15. Doyle, S., EVE Hybrid – 'retro– integration' for a viable, low CO2 vehicle, in proActive. May/June 2007. pp. 13-16.

16. Miller, J.M., Propulsion systems for hybrid vehicles, 2004, Institution of Electrical Engineers.

17. Conte, F.V., Battery and battery management for hybrid electric vehicles: A review, Elektrotechnik und Informationstechnik, 2006, 123(10), pp. 424-431.

18. May, G.J., D. Calasanzio and R. Aliberti, VRLA automotive batteries for stop&go and dual battery systems, Journal of Power Sources, 2005, 144(2), pp. 411-17.

19. Ohmae, T., K. Sawai, M. Shiomi and S. Osumi, Advanced technologies in VRLA batteries for automotive applications, Journal of Power Sources, 2006, 154(2), pp. 523-529.

20. A123 Systems, Mercedes-Benz High Performance Engines, webpage cited 12/05/2013, available from: http://www.a123systems.com/baef9f26-39e3-4173-8d99-fe08ad5130af/download.htm.

21. Bandhauer, T.M., S. Garimella and T.F. Fuller, A Critical Review of Thermal Issues in Lithium-ion Batteries, Journal of the Electrochemical Society, 2011, 158(3), pp. R1-R25.

22. Husain, I., Electric and hybrid vehicles : design fundamentals, 2003, CRC Press.

23. Bonfiglio, C. and W. Roessler, A cost optimized battery management system with active cell balancing for lithium ion battery stacks, Vehicle Power and Propulsion Conference, 2009. VPPC '09. IEEE, 2009.

24. Yufei, C., S. Li and J.W. Evans, Modeling studies on battery thermal behaviour, thermal runaway, thermal management, and energy efficiency, 1996, New York, NY, USA, IEEE.

25. Schweiger, H.-G., O. Obeidi, O. Komesker, A. Raschke, M. Schiemann, C. Zehner, M. Gehnen, M. Keller and P. Birke, Comparison of Several Methods for Determining the Internal Resistance of Lithium Ion Cells, Sensors, 10(6), pp. 5604-5625.

26. Xun, J., R. Liu and K. Jiao, Numerical and analytical modeling of lithium ion battery thermal behaviors with different cooling designs, Journal of Power Sources, 233(0), pp. 47-61.

27. Khateeb, S.A., M.M. Farid, J.R. Selman and S. Al-Hallaj, Design and simulation of a lithium-ion battery with a phase change material thermal management system for an electric scooter, Journal of Power Sources, 2004, 128(2), pp. 292-307.

28. Hashemnia, N. and B. Asaei, Comparative study of using different electric motors in the electric vehicles, Electrical Machines, 2008. ICEM 2008. 18th International Conference on, 2008.

29. Kabasawa, A. and K. Takahashi, Development of the IMA motor for the V6 hybrid midsize sedan, SAE paper 2005-01-0276.

30. Dorrell, D.G., M. Popescu, L. Evans, D.A. Staton and A.M. Knight, Modern Electrical Machine Analysis and Design Techniques Applied to Hybrid Vehicle Drive Machines, Piscataway, NJ, USA, IEEE.

31. Kamichi, K., K. Okasaka, M. Tomatsuri, T. Matsubara, Y. Kaya and H. Asada, Hybrid system development for a high-performance rear drive vehicle, SAE paper 2006-01-1338.

32. Kalan, B.A., H.C. Lovatt, M. Brothers and V. Buriak, System design and development of hybrid electric vehicles, IEEE Annual Power Electronics Specialists Conference, 2002, Cairns, Australia, Institute of Electrical and Electronics Engineers Inc.

33. Fédération Internationale de l'Automobile, FIA WMSC agrees F1 cost cap - Q&A with FIA president [Press release], 17th March 2009, available from: http://www.fia.com/en-GB/mediacentre/pressreleases/wmsc/2009/Pages/wmsc_qa_mm.aspx.

34. Fédération Internationale de l'Automobile, 2011 Formula One technical regulations. 2011.

35. Cross, D. and J. Hilton, High speed flywheel based hybrid systems for low carbon vehicles, IET Conference Publications, 2008, 2008(CP546), pp. 7-7.

36. Greenwood, C., Formula 1 mechanical hybrid applied to mainstream automotive, VDI Berichte, 2008(2029), pp. 711-723.

37. Mraz, S., High-powered hybrids, Machine Design, 2010, 82(8), pp. 20-1.

38. Carpinter, B., Hybrid Le Mans Audi makes history, Motor Equipment News, pp. 34-35.

39. Kovacs, G., D. McGeoch and O. Tur, Potential strategies and technologies of a kinetic energy recovery system for Formula One, International Conference on Automotive Technologies, 2008, Istanbul.

40. Youson, M., The great divide, in Race Tech International. October 2010. pp. 36-40.

41. Hamilton, M., Ferrari outpace Force India to seal win for Kimi Raikkonen, in Guardian. 30th August 2009.

42. Shortlidge, C.C., Control system for a 373 kW, intercooled, two-spool gas turbine engine powering a hybrid electric world sports car class vehicle, Journal of Engineering for Gas Turbines and Power, 1998, 120(1), pp. 84-88.

43. Jost, K., Patriot's hybrid-electric drivetrain, Automotive Engineering International, 1994, 102(12), pp. 30-33.

44. DeLorenzo, M., Modern Chrysler concept cars: the designs that saved the company, 2000, MBI Pub. Co.

45. Boberg, E., Common sense not required: idiots designing cars + hybrid vehicles: my career with Chrysler, 2004, 1st Books Library.

46. Automobile Club de l'Oust, 24 Heures du Mans sporting regulations 2009. 2009.

47. Allen, A., R. Beardmore and R. Nash, Generic integrated systems modelling for low carbon, zero emission and concept, whole vehicle, simulation, IET Hybrid and Eco-Friendly Vehicle Conference, 2008, The Institution of Engineering and Technology.

48. American Le Mans Series, 2010 Petit Le Mans race results. 2nd October 2010.

49. Automobile Club de l'Oust, 24 Heures du Mans sporting regulations 2011. 2009.

50. Endurancesportscar.net, 24 Heures du Mans New - The show starts on 24th April!, webpage cited 29/05/2011, available from: http://www.endurancesportscar.net/24heures/news/2011/2011_0135.html.

51. Watkins, G., Untouchable Audi, impressive Toyota, AutoWeek, 2012, 62(14), pp. 82-83.

52. Strang, S., Spinning the (fly)wheel: Audi's quest for hybrid history, webpage cited 14/04/2013, available from: http://plus.autosport.com/premium/feature/4520/spinning-the-flywheel-audi-quest-for-hybrid-history/.

53. Formula Hybrid, 2011 Formula Hybrid rules. 2011.

54. Benson, K.W., D.A. Fraser, S.L. Hatridge, C.A. Monaco, R.J. Ring, C.R. Sullivan and P.C. Taber, The hybridization of a formula race car, IEEE Vehicle Power and Propulsion Conference, 2005, Chicago, IL, United states, Inst. of Elec. and Elec. Eng. Computer Society.

55. Sibley, J., S.G. Wirasingha and A. Emadi, Formula Hybrid racing at Illinois Institute of Technology: Academic year 2007/2008, IEEE Vehicle Power and Propulsion Conference, 2008, Harbin, China, Inst. of Elec. and Elec. Eng. Computer Society.

56. Wirasingha, S.G., J. Sibley, A.I. Antoniou, A. Castaneda and A. Emadi, Formula Hybrid racing at Illinois Institute of Technology: Design to implementation, IEEE Vehicle Power and Propulsion Conference, 2007, Piscataway, NJ 08855-1331, United States, Institute of Electrical and Electronics Engineers Computer Society.

57. Loveless, E., T. Ludikar, S. Meghnath and P. Sampson, Drive train optimization and control for an open wheel hybrid race car, ENGG 3100: Design III projects, 2007, 2007, University of Guelph.

58. Lukic, S.M. and A. Emadi, Effects of drivetrain hybridization on fuel economy and dynamic performance of parallel hybrid electric vehicles, IEEE Transactions on Vehicular Technology, 2004, 53(2), pp. 385-389.

59. Holder, C. and J. Gover, Optimizing the Hybridization Factor for a Parallel Hybrid Electric Small Car, Vehicle Power and Propulsion Conference, 2006. VPPC '06. IEEE, 2006.

60. Gordon Kirby, Rob Wills on the future of hybrid and electric cars, webpage cited 26/04/2011, available from: http://gkformulahybrid.wordpress.com/2011/04/26/7-rob-wills-on-the-future-of-hybrid-and-electric-cars/#more-132.

61. David Duffy, Drayson to contest electric vehicle race series in The Oxford Times. 23 February 2011.

62. Quentin Spurring, The future of Formula racing? Electric single-seater targets FIA Formula 3 series performance —clocking in at a quiet 0 to 62 mph in just 3 seconds, Tire Business, 2011, 28(21).

63. Formula E News, Formula E orders 42 Cars from Spark Racing Technology, webpage cited 21/04/2013, available from: http://formula-e-news.com/formula-e-orders-42-cars-from-spark-racing-technology/.

64. Joseph, N., Ecclestone moves to establish new GP3 series, webpage cited 03/04/2009, available from: http://www.autoblog.com/2008/08/14/ecclestone-moves-to-establish-new-gp3-series/.

65. Yamakoshi, T., K. Matsumura, Y. Yamakoshi, H. Hirose and P. Rolfe, Physiological measurements and analyses in motor sports: a preliminary study in racing kart athletes, European Journal of Sport Science, 2010, 10(6), pp. 397-406.

66. Backman, J., 2005. Acute neuromascular responses to car racing. Thesis (Master's). University of Jyväskylä.

67. Motorsport Industry Association, Motorsport valley: the business of winning, 2007, GDP:Automotive.

68. Henry, N. and S. Pinch, Spatialising knowledge: placing the knowledge community of Motor Sport Valley, Geoforum, 2000, 31(2), pp. 191-208.

69. Pinch, S. and N. Henry, Discursive aspects of technological innovation: the case of the British motor-sport industry, Environment and Planning A, 1999, 31, pp. 665-682.

70. Henry, N. and S. Pinch, Neo-Marshallian nodes, institutional thickness, and Britain's 'Motor Sport Valley': thick or thin?, Environment and Planning A, 2001, 33, pp. 1169-1183.

71. Foxall, G.R. and B.R. Johnston, Innovation in Grand Prix motor racing: the evolution of technology, organization and strategy, Technovation, 1991, 11(7), pp. 387-402.

72. Ferriss, P., ALMS series goes green with alternative fuels, in The Globe and Mail. 15th May 2008. pp. G6.

73. Crosse, J., Interview: David Richards, Chairman, Prodrive, in Automotive World. 22nd January 2009.

74. Frankel, A., Here's the future - fast, green and dazzling, in The Sunday Times - T2. 7th March 2010. pp. 6-7.

75. Zytek unveiled as parts supplier to McLaren F1 KERS system, in The Independent. 10th August 2009.

76. English, S., Zytek to enter petrol-electric car, webpage cited 02/04/2009, available from: http://www.autosport.com/news/report.php/id/70131.

77. Vehicle & Operator Services Agency, Individual vehicle approval (IVA) manual for vehicle category M1 (passenger vehicles), 2009, Vehicle & Operator Services Agency.

78. Motor Sports Association, Competitors' yearbook, 2007, Royal Automobile Club Motor Sports Association.

79. Motor Sports Association, EV Cup Sporting & Technical Regulations Draft Four. 26th March 2011.

80. Fédération Internationale de l'Automobile - Technical Working Group of the Electric and New Energy Championships Commission, Electric safety for EVs and hybrids, 04th June 2011.

81. ISO 6469, Electrically propelled road vehicles — Safety specification: Part 3: Protection of persons against electric shock. 2010.

82. Premium Automotive Research and Design (PARD), Factors Opportunites and Threats. 2007, Warwick Manufacturing Group, University of Warwick.

83. Premium Automotive Research and Design (PARD), Market Factors (Results). 2007, Warwick Manufacturing Group, University of Warwick.

84. The Society of Motor Manufacturers and Traders, Motor Industry Facts 2010. 2010.

85. Green, P.E., A.M. Krieger and Y. Wind, Thirty Years of Conjoint Analysis: Reflections and Prospects, Interfaces, 2001, 31(3), pp. 56-73.

86. Green, P.E. and V. Srinivasan, Conjoint analysis in consumer research: issues and outlook, The Journal of Consumer Research, 1978, 5(2), pp. 103-123.

87. Orme, B.K., Getting started with conjoint analysis : strategies for product design and pricing research, 2006, Research Publishers, LLC.

88. Dagsvik, J.K., T. Wennemo, D.G. Wetterwald and R. Aaberge, Potential demand for alternative fuel vehicles, Transportation Research Part B: Methodological, 2002, 36(4), pp. 361-384.

89. Ahn, J., G. Jeong and Y. Kim, A forecast of household ownership and use of alternative fuel vehicles: A multiple discrete-continuous choice approach, Energy Economics, 2008, 30(5), pp. 2091-2104.

90. Brownstone, D., D. Bunch, T. Golob and W. Ren, Transactions choice model for forecasting demand for alternative-fuel vehicles, Research in Transportation Economics, 1996, 4, pp. 42.

91. Eggers, F. and F. Eggers, Where have all the flowers gone? Forecasting green trends in the automobile industry with a choice-based conjoint adoption model, Technological Forecasting and Social Change, 2011, 78(1), pp. 51-62.

92. Rafinejad, D., Innovation, Product Development and Commercialization: Case Studies and Key Practices for Market Leadership, 2007, J. Ross Publishing, Incorporated.

93. Eversheim, W., Innovation Management for Technical Products: Systematic and Integrated Product Development and Production Planning, 2009, Springer-Verlag Berlin Heidelberg.

94. Johnson, R. and B.K. Orme, Getting the most from CBC. Technical paper, available from http://www.sawtoothsoftware.com/download/techpap/cbcmost.pdf, 2003.

95. Brownstone, D. and K. Train, Forecasting new product penetration with flexible substitution patterns, Journal of Econometrics, 1998, 89(1-2), pp. 109-129.

96. Cary, T., Ferrari president hits out at new technology in Formula One, in The Telegraph. 12th November 2008.

97. Lambert, S., S. Maggs, P. Faithfull and A. Vinsome, Using conjoint analysis to better understand misconceptions of sustainable vehicle technology use in sports cars, The International Journal of Environmental, Cultural, Economic and Social Sustainability, 2009, 5(4), pp. 1-14.

98. Wipke, K.B., M.R. Cuddy and S.D. Burch, ADVISOR 2.1: a user-friendly advanced powertrain simulation using a combined backward/forward approach, Vehicular Technology, IEEE Transactions on, 1999, 48(6), pp. 1751-1761.

99. Gao, D.W., C. Mi and A. Emadi, Modeling and simulation of electric and hybrid vehicles, Proceedings of the IEEE, 2007, 95(4), pp. 729-45.

100. Van Mierlo, J. and G. Maggetto, Innovative iteration algorithm for a vehicle simulation program, Vehicular Technology, IEEE Transactions on, 2004, 53(2), pp. 401-412.

101. Marco, J., N.D. Vaughan, H. Spowers and M. McCulloch, Modelling the acceleration and braking characteristics of a fuel-cell electric sports vehicle equipped with an ultracapacitor, Proceedings of the Institution of Mechanical Engineers, Part D: Journal of Automobile Engineering, 2007, 221(1), pp. 67-81.

102. Lambert, S., S. Maggs, P. Faithfull and A. Vinsome, Development of a hybrid electric racing car, Hybrid and Eco-Friendly Vehicle Conference, 2008, Coventry, UK, The IET.

103. Charters, D., M. Watkinson, D. Wykes and B. Simpkin, H4V - Hybrid four wheel drive vehicle, 2008, Hybrid and Eco-Friendly Vehicle Conference, Coventry, United Kingdom, Institution of Engineering and Technology.

104. Oxford Yasa Motors, Electric motors spin out secures funding, webpage cited 04/05/2013, available from: http://www.yasamotors.com/node/16.

105. Saab, A., Electronics: Safe Charging, in Appliance Design. 1st June 2007.

106. Min, C. and G.A. Rincon-Mora, Accurate electrical battery model capable of predicting runtime and I-V performance, Energy Conversion, IEEE Transactions on, 2006, 21(2), pp. 504-511.

107. Zhang, C.P., J.Z. Liu, S.M. Sharkh and C.N. Zhang, Identification of dynamic model parameters for lithium-ion batteries used in hybrid electric vehicles, International Symposium on Electric Vehicles 2009, Beijing, China.

108. Dornhege, J., Torque steer influences on McPherson front axles, 2004, Leicestershire, United kingdom, Professional Engineering Publishing.

109. Sawase, K., Y. Ushiroda and K. Inoue, Effect of the right-and-left torque vectoring system in various types of drivetrain, 2007, Hollywood, CA, United states, SAE International.

110. Symonds, P., The critical years, MIA conference "Changes in motorsport: a vision for the future in turbulent times", 2008, Cologne, Germany.

111. Eberle, D.U. and D.R. von Helmolt, Sustainable transportation based on electric vehicle concepts: a brief overview, Energy & Environmental Science, 2010, 3(6), pp. 689-699.

112. Cheli, F., F. Cimatti, Dellach, P. and A. Zorzutti, Development and implementation of a torque vectoring algorithm for an innovative 4WD driveline for a high-performance vehicle, Vehicle System Dynamics, 2009, 47(2), pp. 179-193.

113. EOS Electro Optical Systems, Laser sintering helps improve hybrid car acceleration, in Design Solutions. November 2010. pp. 39.

114. Kimberley, W., WorldFirst hybrid Westfield racing car launched at Goodwood Festival of Speed, webpage cited 2nd September 2011, available from: http://www.racetechmag.com/news/news.php?id=79.

115. Lambert, S., S. Maggs, P. Faithfull and A. Vinsome, Using conjoint analysis to better understand misconceptions of sustainable vehicle technology use in sports cars, Fifth International Conference on Environmental, Cultural, Economic and Social Sustainability, 2009, University of Technology, Mauritius.

116. Farrant, N., 2nd September 2011. Personal communication, Oxford YASA Motors.

117. Foley, I., Racing to a Clean-Tech Future - 5th European Cleaner Racing Conference, 2011, Autosport International.

118. BBC Sport, Formula 1 teams disagree on return of Kers power-boost, webpage cited 02/09/2011, available from: http://news.bbc.co.uk/sport1/hi/motorsport/formula_one/8601425.stm.